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OPERATIONAL FLIGHT EVALUATION OF THE TWO-SEGMENT APPROACH FOR USE IN AIRLINE SERVICE

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16. Abstract

United Airlines, under contract with NASA Ames Research Center, has developed and evaluated a two-segment noise abatement approach procedure for use on Boeing 727 aircraft in air carrier service. In a flight simulator, the two-segment approach was studied in detail and a profile and procedures were developed. Equipment adaptable to contemporary avionics and navigation systems was designed and manufactured by Collins Radio Company and was installed and evaluated in two different B-727-200 aircraft. The equipment, profile, and procedures were evaluated out of revenue service by pilots representing government agencies, airlines, airframe manufacturers, and professional pilot associations. A system was then placed into scheduled airline service for six months during which 555 two-segment approaches were flown at three airports by 55 airline pilots. The system was determined to be safe, easy to fly, and compatible with the airline operational environment.

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TABLE OF CONTENTS

Table of Contents-Cont.

LIST OF ILLUSTRATIONS

LIST OF TABLES

OPERATIONAL FLIGHT EVALUATION OF THE TWO-SEGMENT APPROACH FOR USE IN AIRLINE SERVICE

By: G.K. Schwind, J.A. Morrison,
W.E. Nylen, E.B. Anderson

SUMMARY

The two-segment approach has been previously proven a technically and operationally feasible means of reducing community noise exposure resulting from aircraft landing operations. United Airlines (UA) and Collins Radio Company, under contracts with the National Aeronautics and Space Administration Ames Research Center, developed the equipment and procedures deemed necessary to obtain operational acceptance of the two-segment flight path as a routine way of operating B-727 aircraft on approach and landing.

The procedures which were developed were first evaluated out-of-service by a representative group of industry pilots and then by UA line pilots for six months in regular air carrier service. The consensus of these pilots is that the system provides a safe, easy-to-fly two-segment approach. With proper coordination, the procedure can be integrated into the existing air traffic control environment with negligible impact.

The profile consists of a 6° upper segment with a transition to the conventional instrument landing system glide slope such that the aircraft is stabilized by 500 feet above the field. The two-segment computer calculates the 6° upper segment by using altitude and distance from touchdown. The upper segment can be intercepted at an altitude of 3000 feet or more above the ground at typical final approach speeds. The equipment developed provides full guidance throughout the entire profile.

As a result of a six-month evaluation of the system in revenue service, some significant improvements were made to the equipment which developed it well beyond the prototype stage. The equipment was designed to interface with existing avionics, navigation, and guidance systems. It makes use of current instrument displays and failure annunciations. The competitive market environment should be able to eliminate the few remaining equipment development problems, resulting in a production system fully acceptable for airline retrofit.

It is estimated that dual two-segment installations of this type on UA's B-727-200 fleet would cost about $37 000 (1973 dollars) per aircraft, assuming systems could be installed concurrent with airframe overhauls, and operational and maintenance training could be accomplished with existing recurrent training programs.

INTRODUCTION

Background

Development of technical means to reduce community noise due to aircraft operations in the terminal area is being conducted in two general fields:

1. Modifications in terminal area operating procedures which move the source farther from the noise sensitive community and/or provide for operating the engines in a manner which reduces the amount of noise generated.
2. Jet engine and engine nacelle modifications to reduce the noise generated at the source.

A number of operational procedures which do not require aircraft modifications, but which provide significant relief to some portions of the noise-impacted communities, have been defined and studied. Where practicable, these have been implemented (ref. 1).

Intensive studies are being made to assess the economic impact on the air carriers of engine and nacelle modifications. Concurrent with this effort has been the development and evaluation of operationally safe and acceptable two-segment noise abatement approach procedures and equipment.

In the two-segment approach, the aircraft is guided along a flight path angle ("upper segment") greater than the normal Instrument Landing System (ILS) glide slope angle. A transition is then made to the ILS glide slope at some altitude above the ground which allows stabilization prior to landing. The two-segment approach provides noise abatement both by keeping the aircraft higher above the ground and by allowing reduced engine thrust settings to be used on the steeper flight path (ref. 2).

Initial work by the Federal Aviation Administration (FAA) to develop the guidance and instrumentation required to fly an accurate two-segment approach path demonstrated the feasibility of using barometric altitude and Distance Measuring Equipment (DME*) to establish the upper segment flight path (refs. 3 and 4). Most of the recent development effort and evaluations

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*Except as noted otherwise, "DME" as used in this report will refer to the slant range distance from the aircraft to the DME transmitter collocated with the ILS glideslope transmitter. Other meanings are used in technical descriptions of the system herein; however, in those instances the context will make the meaning of the term obvious.

have been devoted to investigating the technical and operational feasibility of guided flight path modification and developing basic concepts with regard to control laws, types of guidance, and displays (refs. 4-8). These programs have identified a number of features which must be included in a two-segment approach to make it safe and practical in the airline operational environment.

It has been found that precise flight instrument guidance along the transition paths as well as good tracking characteristics along the upper segment are prerequisites to operational acceptability (refs. 4 and 5). Such guidance should prevent overshooting the upper segment, which results in a steeper than desired upper segment, and it should also avoid descent below the standard ILS glide slope, which results in an obvious deterioration in flight safety. Without adequate guidance the lower engine power and the higher rates of descent required to track upper segment might create a condition at glide slope transition which requires large power adjustments resulting in a sudden, short-term increase in noise levels and which also might create a potentially unsafe thrust-lift relationship close to the ground. The altitude of stabilization on the standard ILS glide slope has been identified as a key to pilot acceptance, particularly for approaches under instrument and nighttime conditions (refs. 6 and 8).

Previous flight programs have been conducted under near-ideal daytime weather conditions (refs. 6 and 8), and have not dealt with system failures or widely different airport environments. Investigation into these areas was clearly needed prior to placing any system of this type into regularly scheduled air carrier service.

Objectives

The two-segment approach having been shown technically and operationally feasible, the remaining objective was to fully develop and evaluate the operational procedures and equipment necessary to obtain pilot, airline, and FAA acceptance of two-segment flight paths as a routine way of operating airplanes on approach and landing. This objective required the development of a profile, procedures, and equipment which meet the following criteria:

1. The procedures must be safe.
2. The equipment must provide the precision necessary for use in inclement weather, eventually down to Category II minimums.
3. The system and procedures must be acceptable to the pilot community, particularly with respect to crew workload, adequate instrumentation and guidance, similarity to standard ILS procedures, and annunciation of failures or unreliable guidance.

4. The system and procedures must be adaptable to the existing Air Traffic Control (ATC) environment, particularly with respect to initial approach speed flexibility, variable entry altitudes, and special terminal area entry routes.

5. The approach must provide a meaningful reduction in ground noise level.

6. The equipment developed must minimize the impact of providing two-segment approach capabilities on existing airline fleets.

Program Tasks

The program structure and specific tasks were formulated to develop and evaluate a system and procedure which satisfied the above criteria. Principal program tasks were:

1. Define the system operational requirements. This included a detailed consideration of the system/pilot interface.

2. Define the two-segment equipment/aircraft interface. This included a detailed review of all aircraft system and component modifications necessary to interface with the prototype equipment.

3. Conduct a procedures and profile development evaluation in a B-727-200 Flight Simulator. Analyze the effects of system failures and mismanagement.

4. Install and test the prototype hardware in an evaluation aircraft Confirm simulation results or modify these results as necessary.

5. Conduct an engineering flight evaluation of the two-segment profile and procedures developed in the simulator.

6. Conduct a guest pilot evaluation of the procedures and equipment developed, involving participation by pilots from other air carriers, pilot associations, aircraft manufacturers, and government agencies.

7. Conduct a six-month evaluation of the procedures and equipment using regular UA line pilots in the day-to-day air carrier operating environment.

8. Collect equipment performance data as part of the documentation required for system certification for use in general air carrier service.

9. Determine the implications of equipping the United Airlines fleet of B-727-200's with two-segment avionics.

10. Produce a 16-mm sound color documentary movie and prepare detailed reports on the various program phases.

This report provides descriptions of each of the major program phases and of the equipment, profile, and procedures developed. System performance, pilot acceptability, and other aspects of the two-segment approach which affect airline acceptability are discussed. Supplementary reports of the Simulation, Flight, and Guest Pilot Evaluations provide more detailed descriptions of those phases of the program. (refs. 10, 11 and 12)

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A two-segment approach profile, flight procedures, and guidance equipment which provide significant noise abatement have been developed. The system was evaluated in the airline flight operational environment and determined to be compatible with that environment.

An upper segment angle of 6° is compatible with the B-727-200 performance characteristics. The upper segment may be intercepted from level flight, or at moderate rates of descent or ascent, at any altitude 3000 feet above field level (AFL) or higher which is compatible with ATC. This 6° upper segment intersects the 3.0° ILS glide slope at 740 feet AFL. The height of this intersection varies approximately 40 feet per 0.1° of glide slope angle variation.

The equipment interfaces with existing aircraft avionics, navigation, and guidance systems. It provides smooth guidance for transition to upper segment, accurate upper segment tracking, and a smooth transition to ILS glide slope such that the aircraft is stabilized by at least 500 feet AFL for completion of the approach and landing in the same manner as the pilot would complete an ILS approach.

The two-segment approach procedures evaluated in this program are similar to the standard ILS from a pilot technique and workload standpoint. Airspeed control and instrument scanning increase pilot workload slightly. Workload increase is not significant enough to require autothrottles for the approach. The consensus of the 125 pilots who flew and evaluated the system and procedures is that it is safe for use in instrument conditions, and that it would be acceptable to the pilot community for use in regular air carrier service provided certain tailwind and icing condition limitations are recognized.

The profile and procedures are adaptable to the present ATC environment, but coordination with the FAA controllers is necessary to make the two-segment approach compatible with existing air traffic approach procedures.

Some above-surface tailwind conditions would make the 6° approach unacceptable because they induce unacceptably high rates of descent on the upper segment. Also, the engine power required for tracking the 6° upper segment is too low to maintain full anti-ice capabilities. A two-segment approach system installed in an aircraft must not preclude the pilot's initally selecting, or reverting to, standard ILS capabilities when he encounters such conditions.

The equipment developed to provide the two-segment approach guidance has advanced well beyond the prototype stage. It incorporates safety features which protect against system failure, system mismanagement, and unreliable guidance. The same unreliable guidance and component failure warnings as are used for the standard ILS system are used in implementing these protection features. The equipment performance is good, with accuracies acceptable for use in ceiling/visibility conditions to Category II minimums (100 feet decision height).

Installation of dual systems suitable for use to Category II minimums on UA's fleet of 28 B-727-200 aircraft is estimated to cost $37 000 (1973 dollars) per aircraft. This figure assumes that aircraft out-of-service costs could be minimized by installing the system at scheduled airframe overhaul, and that training in its use and maintenance could be included with regular recurrent training.

Several areas of equipment development are left to be resolved in the competitive market environment to make the equipment acceptable to the airlines. The above installation cost estimate does not include any manufacturer equipment costs which might result from making these product improvements or from further development efforts. Specific remaining equipment development areas include:

a. Integral self-testing capabilities to facilitate timely maintenance action.

b. A means of preventing nuisance disengagements by the below glide slope monitor which does not require radio altimetry.

c. Interface and/or equipment modifications for compatibility with different flight director and autopilot systems.

d. Interface design which will accommodate the differences in logic and display philosophies among the various air carriers.

e. Resolution of potential problems with dual system and Category II autoland installations.

This system interfaces well with existing UA B-727-200 aircraft components. It requires a DME transmitter to be installed at the ILS glide slope transmitter. Such ILS-DME's are not common in present airport installations.

A slight fuel savings due to lower thrust settings on the upper segment than on the standard ILS may be realized. The necessary equipment and data systems required to verify and quantify any such savings were not included as a task in this program.

The flight simulator was an invaluable tool in the development of the two-segment system. There was good correlation of results between the Simulation

and Flight Evaluations. Extension of the results of this program to different aircraft types should be undertaken with careful attention to the different flight characteristics of these aircraft. The B-727 is well-suited to approach path modifications because of its good speed and configuration control characteristics. The results of this evaluation should not be considered directly transferrable to other aircraft types.

Recommendations

Where an extrapolation of the B-727-200 results is made to other aircraft types, results should be verified in a certified flight simulator.

Complete the program currently being conducted in a DC-8-61 using a modified area navigation system to develop two-segment guidance without a collocated ILS-DME or other special ground facilities.

In light of the long-term interest in energy conservation, actively investigate the fuel-saving potential of the two-segment approach.

Evaluate the installation and performance requirements for systems which can be certified for use to Category II weather minimums.

Further investigate potential ATC compatibility problems when using the two-segment approach in visual conditions which emerged in the B-727-200 In-Service Evaluation and other potential problems such as wake turbulence.

PROGRAM DESCRIPTION

General

In view of the program's emphasis on operational rather than engineering aspects of the two-segment approach, a program management structure was developed in UA's Flight Operations Division under Vice President of Flight Technical Services, Howard G. Mayes, to insure that the appropriate consideration was given to safety and pilot acceptance factors in the system and procedures development.

The program was accomplished in five phases:

Equipment and Aircraft Interface Design
Engineering Simulation Evaluation
Engineering Flight Evaluation
Out-of-Service Guest Pilot Evaluation
Six-Month In-Service Evaluation

Equipment and Aircraft Interface Design

Prior to the Simulation Evaluation, technical and operational liaison was established with the equipment contractor to define the equipment/aircraft interface; define operational requirements for equipment, instrumentation, cockpit configuration, etc.; and to identify potential safety problems and define equipment specifications to cope with them. Interface with NASA insured that information from previous programs was used where applicable. The primary avionics design philosophy was to use an analog system which would minimize cockpit instrumentation changes and avoid the necessity to modify the standard autopilot or flight director.

A thorough analysis of normal system operation and the effects of system failures and mismanagement was completed. Normal system operation and annuciation of failures and unreliable guidance were designed to be as similar as possible to the standard ILS approach configuration.

In addition, technical and operational liaison was established with other air carriers, government agencies, aircraft manufacturers, and professional pilot organizations. Through these contacts all segments of the industry were encouraged to provide their technical and operational inputs throughout the program so their specific concerns could be given appropriate consideration.

Engineering Simulation Evaluation

When the system characteristics and aircraft interface were defined, they were programmed into a United Airlines B-727-222 flight simulator at the UA Flight Training Center in Denver, Colorado. This permitted the Project Pilot Team to proceed with the development and analysis tasks at the same time Collins was developing, fabricating, and testing the prototype hardware which was to be installed in the evaluation aircraft. It also facilitated certain investigations into profile and procedures development not possible in the aircraft.

The primary objective of the Simulation Evaluation was to define a narrow set of profiles and operational procedures which could be readily refined and optimized in the evaluation aircraft. The simulation evaluation included a detailed study of the effects of varying the profile parameters shown in Figure 1*, and an in-depth evaluation of the effects of system failure and mismanagement which, in some extreme cases, could not have been safely tested in the aircraft without first determining the total effects of such failures in the simulator. The simulator was an invaluable analysis and development medium for these tasks. It permitted "instant replay" of any trial or trials under the same or precisely modified conditions. It was particularly valuable in providing exact and repeatable environmental conditions so the effects of various profile or procedures changes could be determined.

Each of the profile variables was independently investigated in detail for its effect on safety, repeatability, pilot workload, and ground noise level. Practical maximum and minimum values were established for each parameter. Maximum and minimum practical airspeeds for intercepting, tracking, and transitioning onto the profile were also investigated with regard to established configuration schedules, crew workload, and effect on ground noise level. In addition, the effects of varying environmental conditions were investigated to determine the manner in which they affect (or degree to which they limit) the two-segment approach differently than they would affect (or limit) the standard ILS procedure under the same conditions. The profile variables were then combined to develop a small family of two-segment profiles of approximately equal operational and noise abatement merit.

Several data systems were developed to provide the means to analyze simulation evaluation results.

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* Angles of approach paths are exaggerated by 3 to 8 times in illustrations throughout this report for clarity.

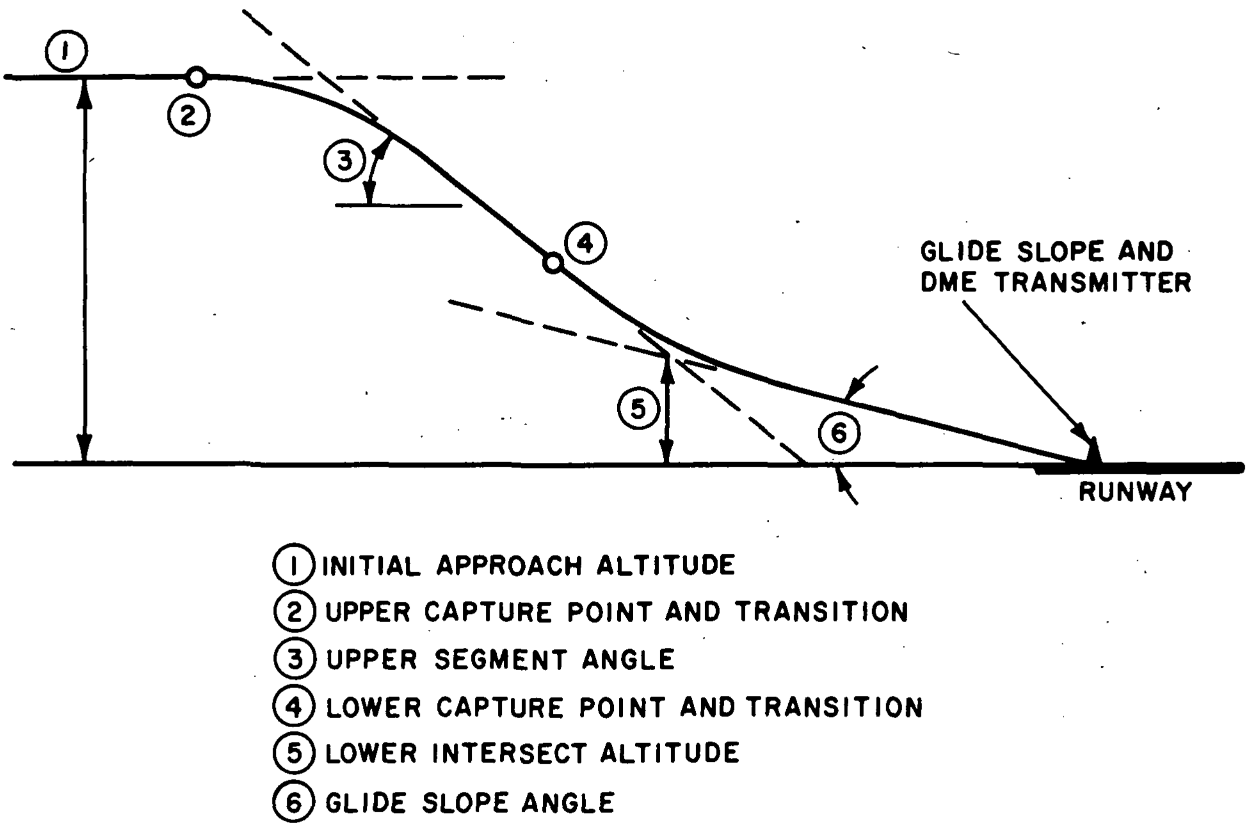


Figure 1 - Two-Segment Approach Profile Variables

Centerline and contour noise prediction programs using X-Y plots previously developed for the study of noise abatement takeoff procedures were used extensively to quantify the effect of the various profile and procedure changes on ground noise levels. Although not developed to yield accurate absolute noise level predictions for correlation with actual field measurements, these programs were vital to the development and optimization investigations since they provided estimates of noise level differences between different approach profiles.

A 14 channel oscillograph was used to record a set of parameters focusing on pilot performance on the two-segment profile. It proved to be an extremely effective analysis tool in the developmental phase of the program.

The simulator digital line printer was modified to provide real-time data output of 15 parameters every second. Six parameters were plotted in graphical form and nine were tabulated. These focused on aircraft performance and pilot workload, and were presented with resolution not available with the oscillograph to permit comprehensive analysis of specific approaches.

Approach data cards provided the means by which pilot comments regarding each approach were recorded as the approach was flown. In addition, a comment summary sheet was used to summarize the work accomplished during a given simulator period.

One hundred seventy-five hours of simulator flying time were used to accomplish the Simulation Evaluation objectives. At the conclusion of the simulation evaluation, the mechanics of the two-segment approach were well understood, and the profile and procedures had been developed sufficiently to test the results in actual flight.

Engineering Flight Evaluation

The primary objective of the Engineering Flight Evaluation was to determine if the two-segment profile, procedures, and equipment which had been developed were operationally sound under the flight conditions expected to be encountered in line service. To accomplish this, the evaluation was divided into several specific areas of investigation:

1. Verification of the operation of the two-segment avionics installed on the aircraft.
2. Evaluation of normal two-segment system equipment and development of nominal profile and procedures.

3. Evaluation of the need for an autothrottle system for two-segment approaches.

4. Investigation of abnormal procedures and operation of equipment, including abused approaches and malfunctions of airborne and ground equipment.

5. Determination of the accuracy capabilities of the equipment.

The evaluation was conducted in two aircraft. The equipment was first installed in a B-727-277 leased from Ansett Airlines of Australia. The installation was certified for non-revenue operations under Federal Air Regulations (FAR) Part 91 and Civil Air Regulations (CAR) Part 375 by a Supplemental Type Certificate (STC) issued by the FAA under FAR Part 21. Two hundred forty-five approaches, 196 of them two-segment, were flown in the Ansett aircraft in the Engineering Flight Evaluation. In addition, it was used for most of the Out-of-Service Guest Pilot Evaluation. When the Ansett aircraft was released from the program in February, 1973, the two-segment system was operational and ready for the line service evaluation.

In April, 1973, the equipment was installed in a United Airlines B-727-222 and certified by STC under FAR Part 21 for revenue service under FAR Part 121. Prior to the in-service period, however, additional engineering flight evaluation was necessary due to some changes in the Collins equipment required for line service, substantial differences in aircraft interfaces between the UA and Ansett aircraft, and in recognition that more rigorous certification standards applied to the system for use in revenue service. One hundred thirty-two additional out-of-service approaches, including 102 two-segment approaches, were made in the UA aircraft during this phase.

The primary data system used was a digital flight data recorder. This system, which was installed in both aircraft, consisted of off-the-shelf components designed for regular airline service. The system recorded 90 parameters in serial-digital format. Data cassettes were transcribed and processed by United Airlines and data was printed in several formats. Each format provided parameters to meet the needs of various data users. An operational printout provided for use by the Project Pilot Team included the same data in the same format as was provided by the simulator line printer, focusing on pilot workload and performance. A concept evaluation printout included parameters primarily necessary for technical evaluation of the approaches. An equipment evaluation printout was provided primarily for use by Collins Radio Company in evaluating the performance of the two-segment avionics.

An oscillograph recorder was mounted in the cabin of the Ansett aircraft. It served as a back-up to the digital recorder system and provided for immediate in-flight analysis of approach data. (Details of both the digital and oscillograph recorder systems, including samples of digital printouts, are contained in ref. 11.)

Approach data cards were used by the Project Pilots to describe the objectives and record the results of each approach flown. Each card described one approach in terms of profile geometry, flight parameters, and test objectives and provided space for recording specific data and comments regarding the approach.

A portable video-tape recorder was used in the Engineering Evaluation and certification flights of the UA airplane. Recordings of the Captain's instrument panel during the approaches provided an excellent means to verify system performance and observer comments, analyze failure modes and abnormal operations, and assist in troubleshooting problems encountered during avionics verification flights. The sound track provided an accurate record of real-time flight crew comments. Video recordings made during the Engineering Evaluation were accepted by the FAA as sufficient documentation of certain system behavior, thereby significantly reducing the testing necessary on certification flights.

Noise measurements of approaches were made during the Engineering Evaluation by Hydrospace Challenger, Inc. Noise measurements of 49 approaches were made of the FAR 36 qualified Ansett airplane, which was equipped with acoustically treated JT8D-15 engines (ref. 15). Measurements were made of 30 approaches by the UA airplane, which had non-treated JT8D-7 engines (ref. 16). The Government provided precision radar tracking used in conjunction with noise measurements and profile development.

The principal evaluation airport was Stockton, California. NASA installed a DME transmitter collocated with the glide slope on Stockton runway 29R. Reno, runway 16, was used as an alternate evaluation airport. It was equipped with a fully commissioned collocated DME. NASA provided a DME collocated with the glide slope at San Francisco, runway 28L to permit its use for evaluation of approaches into high density air traffic situations at the conclusion of each evaluation flight. Demonstrations of the system were also made at Los Angeles, runway 25L, for FAA Western Region personnel.

Out-of-Service Guest Pilot Evaluation

Fifty-seven pilots from government agencies, aircraft manufacturers, professional pilot associations, and from thirteen air carriers evaluated the equipment, optimum profile, and procedures during the Out-of-Service Guest Pilot Evaluation. (Table I)

Table I - Organizations Represented in the Out-of-Service Guest Pilot Evaluation

American Airlines	Air Line Pilot Association
Ansett Airlines of Australia	Air Transport Association
Braniff International Airways	Allied Pilots Association
Continental Airlines	Boeing Aircraft Company
Delta Airlines	Douglas Aircraft Company
Eastern Airlines	Federal Aviation Administration
Lufthansa	National Aeronautics and Space Administration
Northwest Airlines	U.S. Air Force
Pan American World Airways	
Pacific Southwest Airlines	
Trans World Airlines	
United Airlines	
Western Air Lines	

In most cases the guest pilots participated in a two day program. They were briefed by a Project Pilot, shown an audio visual package, and then flew a syllabus of familiarization approaches in the simulator in Denver. The simulator session included 11 approaches intermixing standard ILS with two-segment approaches under varying weather conditions. During their second day the guest pilots flew the aircraft for a syllabus of 8 approaches at Stockton or Reno.

Previously described simulator and aircraft data systems were used to document each pilot's approaches. In addition, questionnaires were completed by the guest pilots, one after the simulator session and another after the flight. When possible, the same Project Pilot accompanied the guest pilot through both phases of his participation to discern differences between performance in the simulator and performance in the aircraft.

Although recommended procedures were provided, guest pilots were encouraged to try their own particular procedures and techniques with the two-segment approach to evaluate the adaptability of the approach to the operating procedures differences among various air carriers.

Over 300 two-segment and 100 standard ILS approaches were flown by the guest pilots in the aircraft. In addition to the questionnaires, guest pilots volunteered numerous comments throughout the Out-of-Service Evaluation. To assure that all significant opinions were fairly reported, the results and conclusions of the Guest Pilot Evaluation were provided to participating pilots for review and comment prior to publication.

Actual instrument conditions were experienced on three days during the Guest Pilot Evaluation. The reported ceiling on these days ranged from 200 to 350 feet. Forty-eight approaches were made in these conditions in which the transition to the glide slope was completed before the aircraft had descended to the reported ceiling.

In-Service Flight Evaluation

On April 29, 1973, the United B-727-222 began flying a closed loop routing pattern on the West Coast to evaluate the system in line service. The schedule provided for five potential two-segment approaches each day: two each at San Francisco and Los Angeles and one at Portland. More than 700 approaches of all types were made at these airports during the six-month evaluation. Crew scheduling and qualification, weather, air traffic patterns, and two-segment avionics and ground facilities malfunctions reduced the actual number of documented two-segment approaches to 555.

The two-segment system installed and certified for service on the aircraft included several modifications which had been developed as a result of the Engineering and Guest Pilot Evaluations in the Ansett aircraft. These modifications were designed to cope with certain unacceptable or undesirable operational anomalies. Variable components in the equipment which had been provided to change profile geometry during the Flight Evaluation were replaced with fixed-value components corresponding to the optimized profile values.

The only weather limitations set by the FAA in the In-Service Evaluation were that the aircraft was not approved for Category II approaches and two-segment approaches were not authorized for use in icing conditions. United

Airlines limited two-segment approaches to "glide slope out" minimums for the evaluation. Decision heights for these minimums were 534 feet at Portland, 430 feet at San Francisco, 360 feet at Los Angeles. During the In-Service Evaluation, 65 two-segment approaches were initiated in reported instrument conditions, i.e., visibility less than 3 n.mi. or ceiling 1000 feet or less. The transition to the glide slope typically began about 900 feet AFL; 40 approaches were made with the ceiling at or below this level. On 21 approaches, glide slope transition had been completed before the aircraft had descended to the reported ceiling.

Two methods were used to qualify pilots participating in the In- Service Evaluation. Some had a briefing, which included a specially prepared audio-visual presentation of the equipment and procedures, and a simulator period during which approximately six approaches were flown. These pilots were then observed for one approach in-service by a qualified Flight Manager. Other pilots were shown the audio-visual presentation and were then observed for three approaches in-service by a Flight Manager.

Fifty-five line pilots flew two-segment approaches during the In-Service Evaluation. They came from the Los Angeles, San Francisco, and Denver pilot domiciles. Pilots were assigned to the route through United Airlines' normal bidding and award procedures, and in general changed each month.

An observer familiar with the system was on-board the aircraft whenever two-segment approaches were flown. For each approach, observers completed one questionnaire regarding the type of approach and the conditions under which it was made. They also administered a questionnaire to the pilot to obtain his opinions regarding the approach, and completed a third form evaluating the autopilot performance when ever auto-coupled approaches were made. The observer also maintained a log of approaches made, and provided liaison with the program office regarding system maintenance and status of any problems encountered. The digital data recording system provided the same detailed information from this phase as was provided during out-of-service evaluations. As with the Guest Pilot Evaluation, the summary of conclusions from the pilot questionnaires was provided for review and comment by all participants to assure that the conclusions were consistent with the views of the majority of the participating pilots.

Data from the In-Service Evaluation was continuously evaluated to develop any equipment and procedural refinements required to improve system performance. Continuing liaison with ATC personnel was maintained to facilitate the smooth integration of two-segment approaches into the conventional terminal area and approach environment.

A separate Government contractor made noise measurements of the aircraft at Los Angeles for two weeks during the In-Service Evaluation. Comparative measurements were made of the two-segment aircraft and aircraft making standard ILS and non-precision Visual Flight Rules (VFR) noise abatement approaches (ref. 17).

Two-Segment Approach Avionics

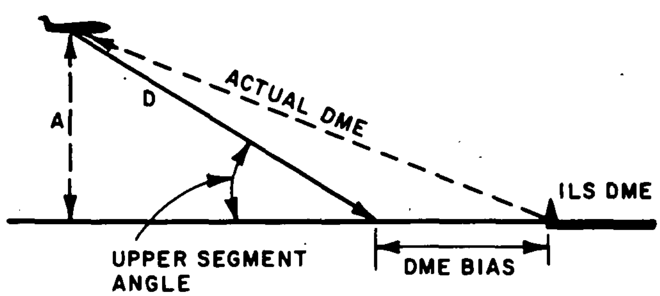
The two-segment avionics system, designed and manufactured by Collins Radio Company, consists of four components:

1. Two-Segment Computer
2. Two-Segment Switching Unit
3. Airport Elevation Set Panel
4. Two-Segment Selector Switch

The two-segment computer is the heart of the system, providing all necessary guidance and deviation information to the existing aircraft systems, i.e., flight director, autopilot, and deviation displays. Primary data inputs to the computer are DME, altitude, and ILS glide slope. The desired upper segment path is determined by the computer as a distance-from-touchdown (DME) and altitude-above-field-level (AFL) locus which meets the criterion

$$\frac{\text{AFL}}{\text{DME - bias}} = \sin\text{(Upper Segment Angle)}$$

The bias, in effect, moves the upper segment away from the runway so it intersects the glide slope prior to touchdown; the greater the bias, the farther from touchdown this intersection will occur (Figure 2). The standard ILS glide slope is the lower segment.



A = Altitude above field elevation
= Baro-corrected pressure altitude minus field elevation (set in the Airport Elevation Set Panel)

D = Distance to intersection of upper segment with field elevation
≅ Actual DME minus DME bias (for small angles)

Fly to maintain $\frac{A}{D}$ = sin (Upper Segment Angle)

Figure 2 - How the Upper Segment Flight Path is Computed

The primary computer outputs are transition guidance and tracking deviation information to the flight director and/or autopilot, vertical deviation from the upper segment for display on the Horizontal Situation Indicator (HSI) (Figure 3) and an optional incremental speed bias to the autothrottle system until the glide slope is captured.

The computer monitors essential aircraft component validity signals. These are required as a prerequisite to initial arming and as a condition for continuing normal operation throughout the approach. Failing any of these validities, it causes the appropriate failure flag (s) to be displayed; and if the flight director and/or autopilot are utilizing the computer output for guidance, it will cause the flight director command bars (Figure 3) to be biased from view and/or the autopilot to be disengaged.

The system was also designed to prevent procedural or input data abnormalities from providing guidance in unsafe situations. It will prevent an attempt to capture the upper segment if the system is configured after passing the normal upper segment capture point, which would result in overshooting the upper segment. If past the upper segment, it will not attempt to capture from above, which would result in a steeper than desired flight path angle. The system also prevents arming for upper segment capture after having captured the standard ILS glide slope.

During the In-Service Evaluation several crews encountered problems when making two-segment approaches in Los Angeles after following a terminal arrival route which passed the airport on a downwind leg prior to turning back to make the approach. Study of the recorded digital data from these occurrences revealed that the two-segment system was being disrupted by passing through the upper segment on the downwind leg while armed, in much the same manner as ILS capture can occur when flying downwind with the ILS system configured for final approach. A computer modification was made which allowed the system to be armed on a downwind leg without encountering this effect. Subsequent operation in line service under the same conditions verified that the modification had corrected this problem.

Erroneous input data can cause the upper segment to be mispositioned with respect to the runway. Such situations were simulated during the evaluation by missetting the airport elevation panel, but any of several electrical or mechanical failures could have the same result.

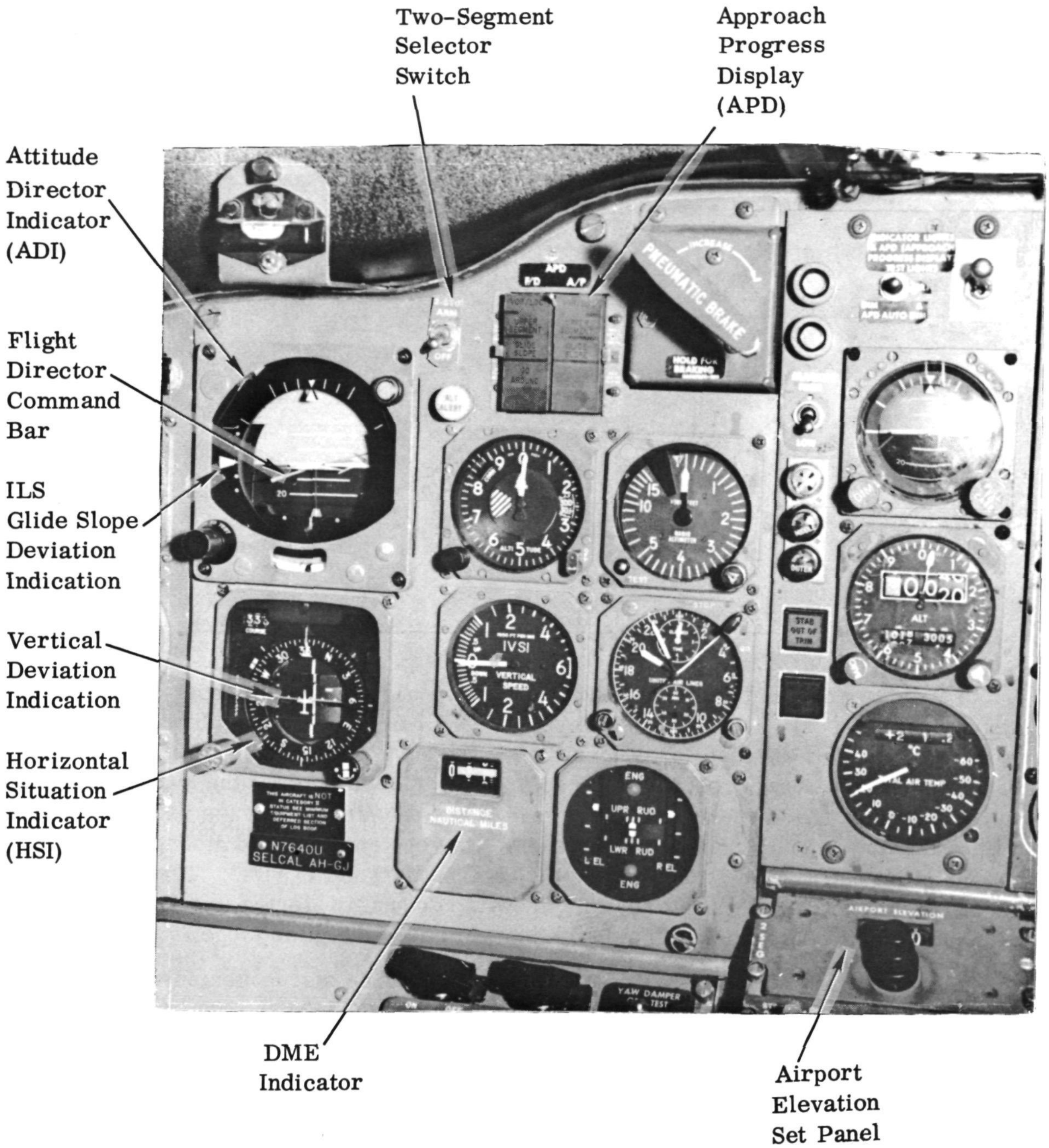


Figure 3 - Captain's Instrument Panel (UA aircraft)

If the upper segment is mispositioned away from the runway, then upper segment capture could actually occur below the standard ILS glide slope, or the upper segment could pass through the glide slope prior to reaching the glide slope arm point (Figure 4). Computer circuitry protects against both of these situations by preventing the system from providing upper segment flight path guidance if the aircraft is below the standard ILS glide slope for more than 10 seconds. In situation 4(a), the system disengages the autopilot and biases the flight director command bars out of view at the upper segment capture point. In situation 4(b), the same results occur 10 seconds after passing through the ILS glide slope.

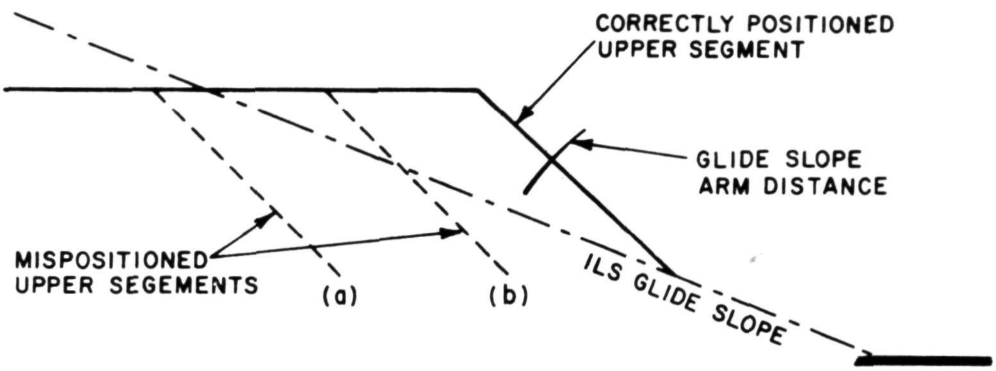


Figure 4 - Upper Segment Mispositioned Away From Runway

Two independent monitors protect against the case where the upper segment is mispositioned towards the runway. All two-segment guidance will be removed if the aircraft is less than 500 feet AFL or within 1.8 n. mi. of the touchdown zone without having captured the glide slope. If the system fails to capture the glide slope for any reason and the aircraft comes to within 1/2 dot (37.5 microamperes) above it, the system will also disengage the autopilot and bias the flight director command bars out of view. These three safety protectors assure that the crew is adequately alerted to take alternative action prior to any potential descent below the glide slope.

During the In-Service Evaluation numerous nuisance disengagements were experienced on approaches into San Francisco. Study of the recorded digital data from these approaches revealed that the "below glide slope" protector was being activated by erratic glide slope information in the region of the null between the actual glide slope and the first reverse sensing false lobe (Figure 5). Traffic ahead on the approach path or on the ground in front of the ILS transmitter disturbed this null in such a way that the aircraft received "fly up" (i.e., "aircraft below glide slope") information even though it was not in a "fly up" region of the normal glide slope pattern. This problem was not encountered during out-of-service flying when air traffic was light. It occurred only at San Francisco during the In-Service Evaluation due to the

lower glide slope beam pattern (2.7° vs. 3.0° at Los Angeles and Portland) and high initial approach altitudes (4000 or 6000 feet at San Francisco vs. 3500 or 4000 feet at Los Angeles and Portland). An additional input signal was required in order to prevent nuisance disengagements but at the same time maintain the valid below glide slope protection provided by the system.

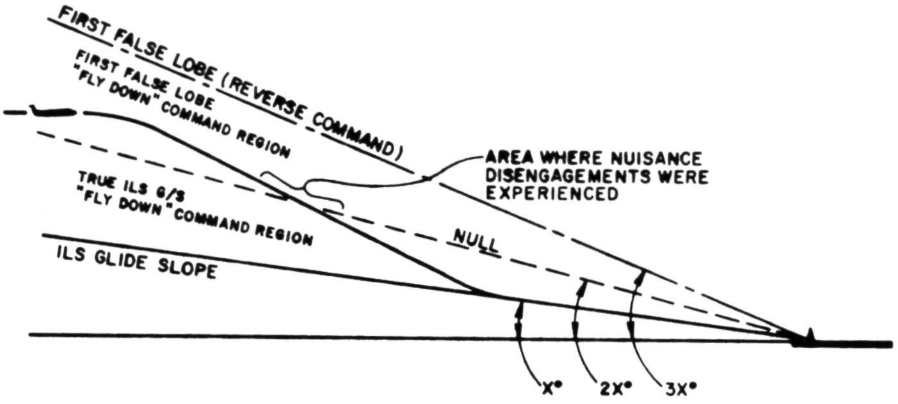


Figure 5 - Nuisance Disengagement due to "Below Glide Slope" Protector

The only effective modification which could be found within the time constraints of the program was to use radio altimetry to inhibit disengagement whenever the aircraft was within 14 n. mi. of touchdown and above 2500 feet radio altitude. Two aspects of this solution make it undesirable as a permanent feature. First, many aircraft in commercial service are not equipped with radio altimeter systems; and second, it requires that the obstruction clearance plane, which is presently defined out to 8.2 n. mi. from the runway, be extended out to 14 n. mi. This is one major design limitation which should be resolved in the competitive market environment.

The two-segment switching unit is the input/output control device for the two-segment computer. The unit consists primarily of logic-controlled relays and is powered only when the two-segment system is armed by the pilot. When unpowered (two-segment selector switch OFF), all relays relax and the standard aircraft systems interface is intact; when powered (two-segment selector switch ARM), the aircraft systems interface is modified such that the computer receives essential data and validity inputs and makes the required computational and logic outputs available to the appropriate systems and instrument displays. The operational integrity of the switching unit is continually monitored as part of the system's self-monitoring functions.

The airport elevation set panel (Figure 3) is set by the pilot to the published touchdown zone elevation to the nearest 10 feet. This, together with barometric altimetry information, makes it possible for the system to determine altitude above field elevation and thus provide the same two-segment profile geometry regardless of varying field elevations.

The two-segment selector switch (Figure 3) is the means by which the pilot selects guidance information for a two-segment approach rather than a standard ILS approach. As previously noted, in the OFF position, the aircraft guidance and instrumentation operate in all respects as though the two-segment system is not installed. In the ARM position, however, the two-segment information is computed and made available for use by the flight director and/or autopilot. The switch may be returned to the OFF position at any time to restore the normal aircraft systems interface.

Interfacing Aircraft Displays and Systems (Figure 6)

The system is designed to use either baro-corrected pressure altitude or uncorrected pressure altitude and a separate baro-correction signal, whichever can be provided by the aircraft altimetry systems. The prototype hardware, however, was designed to accept altimetry information only as dc signals. This presented problems in installing the system on aircraft where the standard ARINC* format of electrical altitude information is coarse-fine synchros. On both evaluation installations this incompatibility required the installation of an electric standby altimeter designed to accept the standard aircraft altimetry information and convert it to the necessary dc input to the two-segment system.

The system is designed to use DME in the pulsed pair output format of an ARINC 568 DME system. The Ansett aircraft was equipped with such a system, but the UA aircraft had ARINC 521 systems. Collins Radio Company modified the ARINC 521 system to provide an output in the ARINC 568 format. A modified ARINC 521 system was used in the In-Service Evaluation.

The standard ILS glide slope information, which is displayed on the Attitude Director Indicator (ADI) at all times during the approach, is the third and last of the primary data inputs to the system. To avoid potential display switching transients during the transition from the upper segment to the glide slope, the glide slope information is provided to user systems by the two-segment system.

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*ARINC - Aeronautical Radio, Inc. - The means by which the aviation industry provides various standards for airborne equipment.

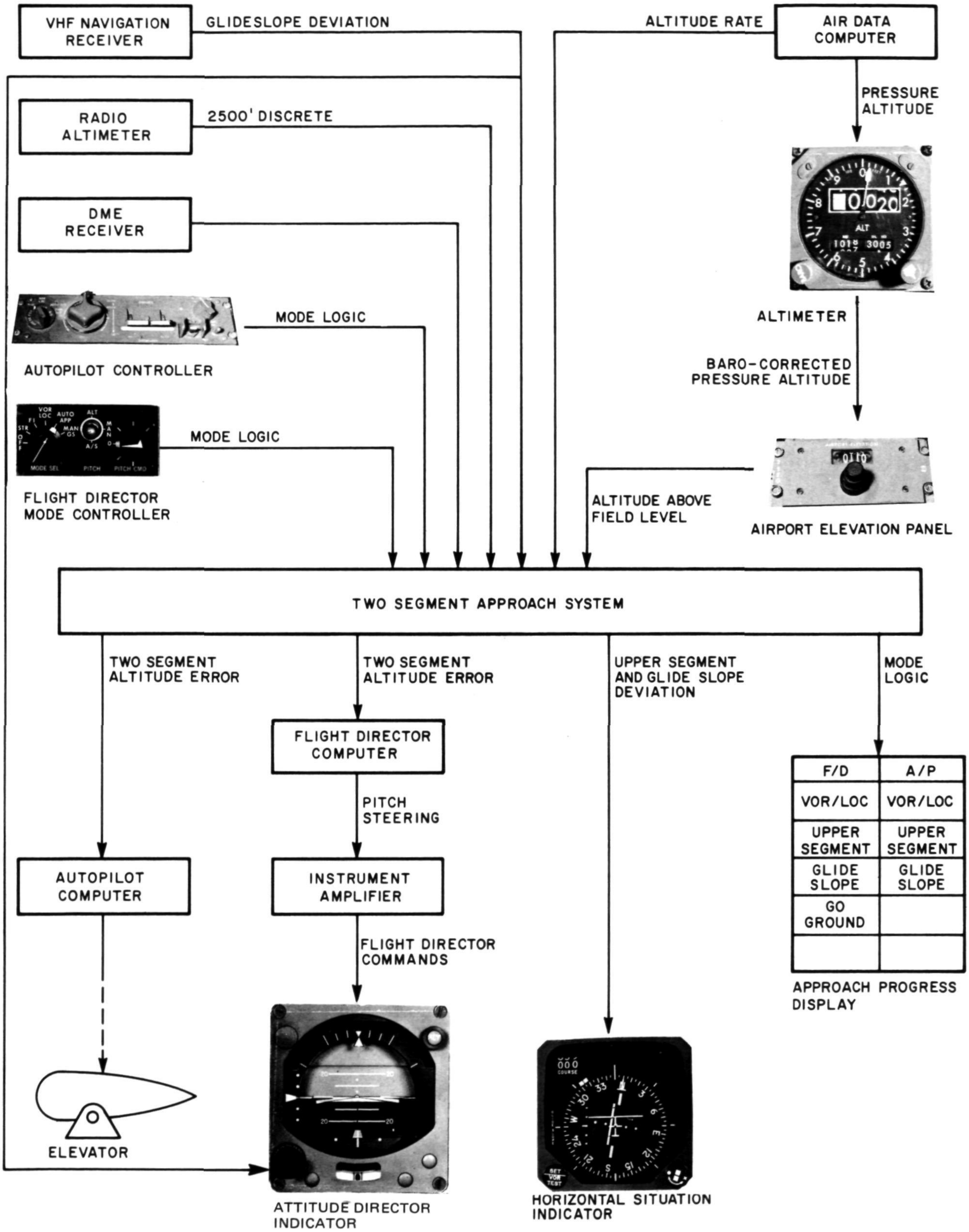

Figure 6 - Aircraft/Two-Segment Approach System Interface (UA aircraft) showing signal paths when two-segment system is armed and operating

Two secondary data inputs are required by the system. Altitude rate information from the air data system is used for damping the vertical tracking guidance. Radio altitude is used to set one of the safety monitors as discussed above.

The primary user systems of the information made available by the two-segment system are the flight director and autopilot. The two-segment system is designed such that no modification to the flight director or autopilot is required to utilize the transition and tracking information provided by the computer. To use the information, the system(s) must be set to the appropriate auto approach mode(s). When in auto approach, with the two-segment system armed, the pitch channels of the respective systems utilize the upper segment vertical deviation information in the same way they utilize altitude hold deviation information when the two-segment system is off.

The flight director/autopilot approach progress display (Figure 3) is modified to annunciate UPPER SEGMENT arm (amber light) and capture (green light) in the same manner in which GLIDE SLOPE arm and capture functions are annunciated on normal ILS approaches.

The two-segment system is designed to interface with an autothrottle system if desired. Autothrottles were evaluated on the Ansett aircraft but were not installed on the UA aircraft based on the results of the Engineering Flight and Guest Pilot Evaluations. If autothrottles are installed, the two-segment system is designed to provide an incremental speed bias to the autothrottle system on the upper segment if operationally desired.

The only two-segment system interface with any lateral control functions of the aircraft is to provide a revised gain programming trip point for autopilot localizer tracking. Localizer capture is not a prerequisite to upper segment capture or tracking.

PROFILE

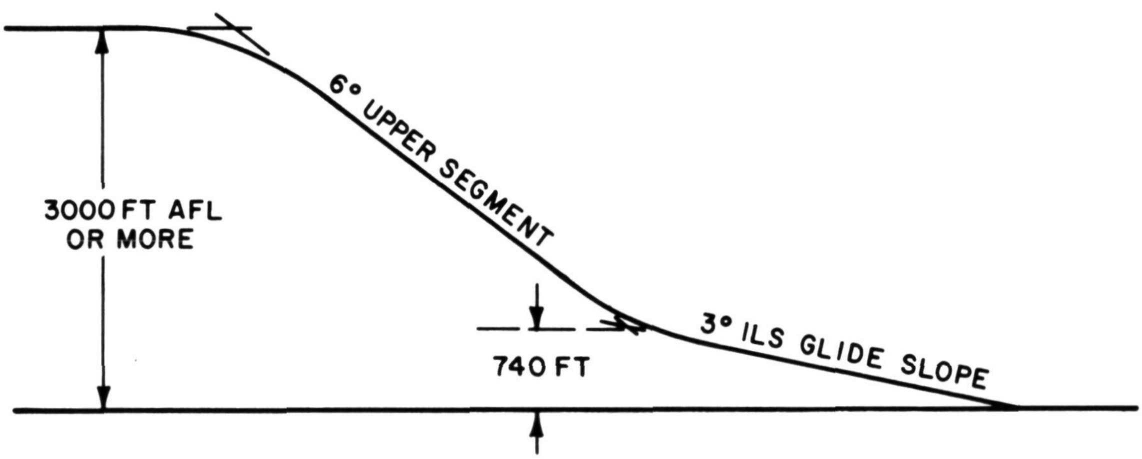

Figure 7 - Optimum B-727 Two-Segment Approach Profile with 3° ILS Glide Slope

Initial Approach Altitude

The minimum altitude at which the upper segment should be intercepted was established for both operational and noise abatement reasons. From a safety and crew workload standpoint, it was considered necessary to intercept the upper segment high enough to allow stabilization on the upper segment prior to commencing the transition to the ILS glide slope. The initial approach altitude also had to be high enough to provide significant noise abatement. The minimum altitude which met these criteria was 3000 feet AFL.

Higher initial approach altitudes provide additional noise abatement and a longer stabilization on the upper segment. The necessity to have flexibility in the ATC environment dictated that the equipment not restrict initial approach to the upper segment to a specific altitude. The capability to start the approach at any altitude up to 12 000 feet MSL was provided. This upper limit was due to the interface of the standard aircraft coarse-fine synchro altimetry with the prototype equipment which only accepted dc altitude information. Coordination with ATC revealed that 3500 or 4000 feet AFL initial altitudes were adaptable to existing traffic procedures. Capture of the upper segment at these altitudes occurred at 6.6 to 7.4 n. mi. from touchdown, and ATC gave the two-segment approach aircraft the same intercept of the final runway heading normally used under instrument conditions (about 8 n. mi. from touchdown) which permitted lateral stabilization prior to the pitch over to capture the upper segment. Somewhat higher altitudes can be accommodated for straight-in approaches, but when the aircraft is making a 180° turn onto the final approach heading these higher initial altitudes could result in a delay and problems for ATC because a longer than usual downwind leg is required. Initial altitudes above about 6000 feet present coordination problems with ATC due to the current airspace structure. The descent starts at a much greater distance from the airport and passes through altitudes controlled by center, approach, and tower controllers. At these altitudes and ranges from the airport it is also usually desired to keep airspeed high.

Upper Capture Point and Transition

The transitions to the upper segment and glide slope are of upmost importance in obtaining pilot acceptance of the two-segment approach. If these transitions can be completed without any significant change in flight technique, the two-segment concept should be acceptable as operationally sound. The transition to the upper segment should occur such that there is negligible overshoot. To do this consistently under all expected conditions, capture occurs as a function of the rate of closure to the upper segment as well as the actual displacement from it. If the initial airspeed is high, if there is a tailwind, or if the aircraft is climbing, the upper capture point will occur earlier than if there is a headwind or a rate of descent (Figure 8). This provides similar transitions over the range of expected operational conditions.

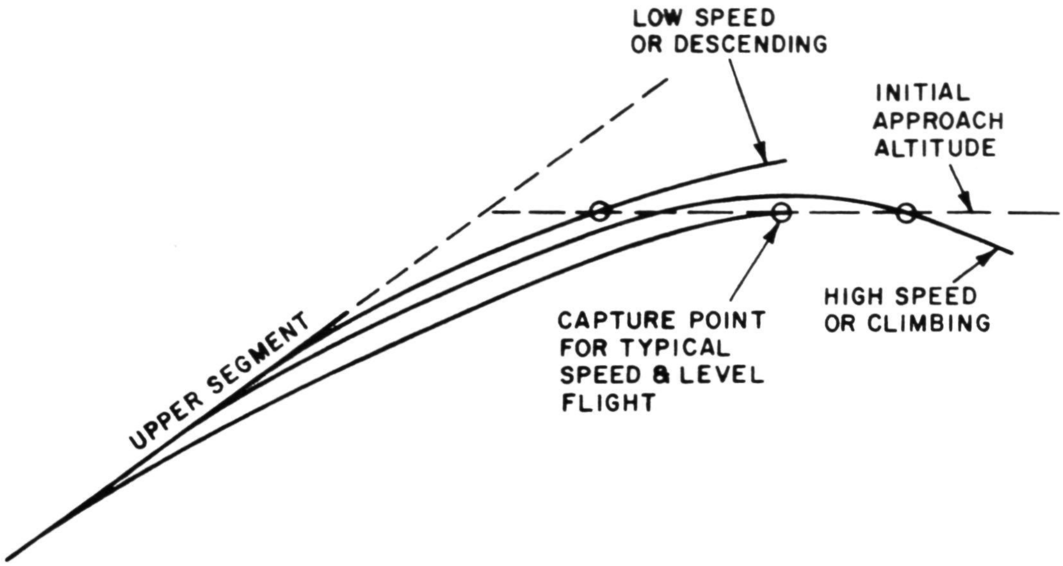

Figure 8 - Upper Transitions
showing variable upper segment capture points

The upper capture from level flight in still air at 160 knots indicated airspeed occurs when the aircraft is about 450 feet below the upper segment. In the Simulation Evaluation this was varied from 100 to 600 feet, with the transition times varied accordingly. The transition developed is smooth, and easy for the pilot or autopilot to fly. The aircraft is pitched over slowly and smoothly, and the transition to the upper segment is completed about 150 to 350 feet below the initial approach altitude.

Upper Segment

Upper segment angles from 4° to 10° were investigated during the simulation evaluation. Larger angles produce noise abatement advantages due to higher flight path altitudes (Figure 9)*. From the operational standpoint, however, relatively small variations in upper segment angle introduce airspeed, configuration, power, and vertical speed differences which are critical to safety, repeatability, workload, and pilot acceptance. The practical range for investigation during the Flight Evaluation was 5.2° to 6.5°. Within this range changes in angle affect operational considerations much more than they affect noise abatement advantages.

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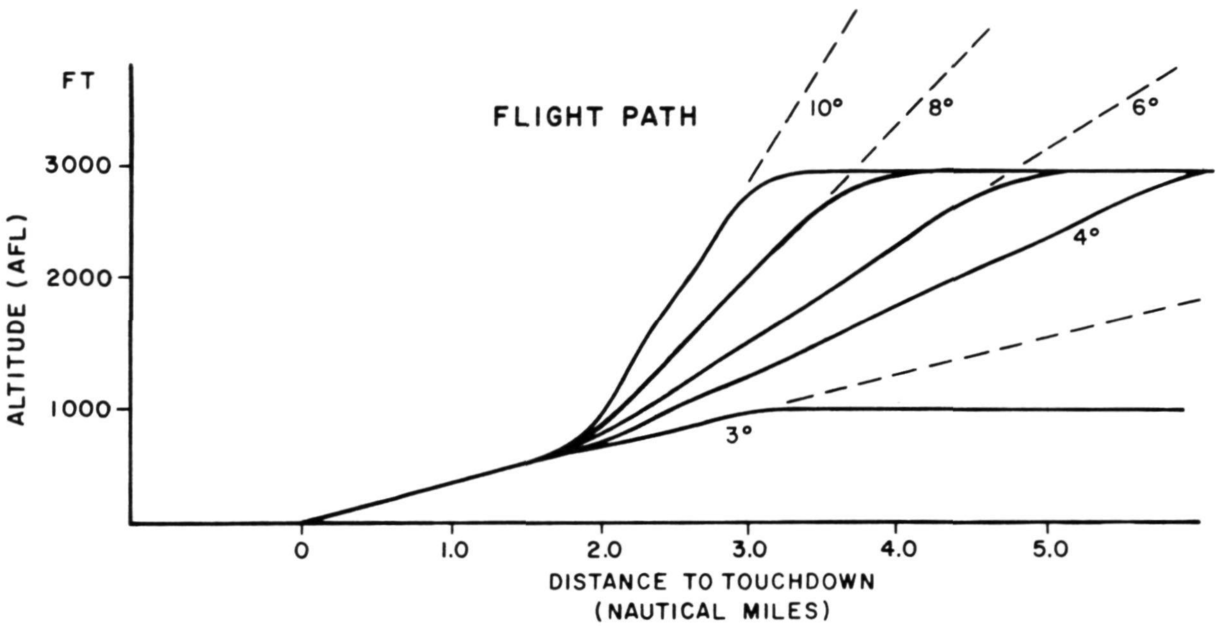
* Discontinuities in noise traces at upper transition (Figures 9 and 11) are due to simulator data system dynamic response characteristics, and are not representative of what would be expected in actual field noise measurements.



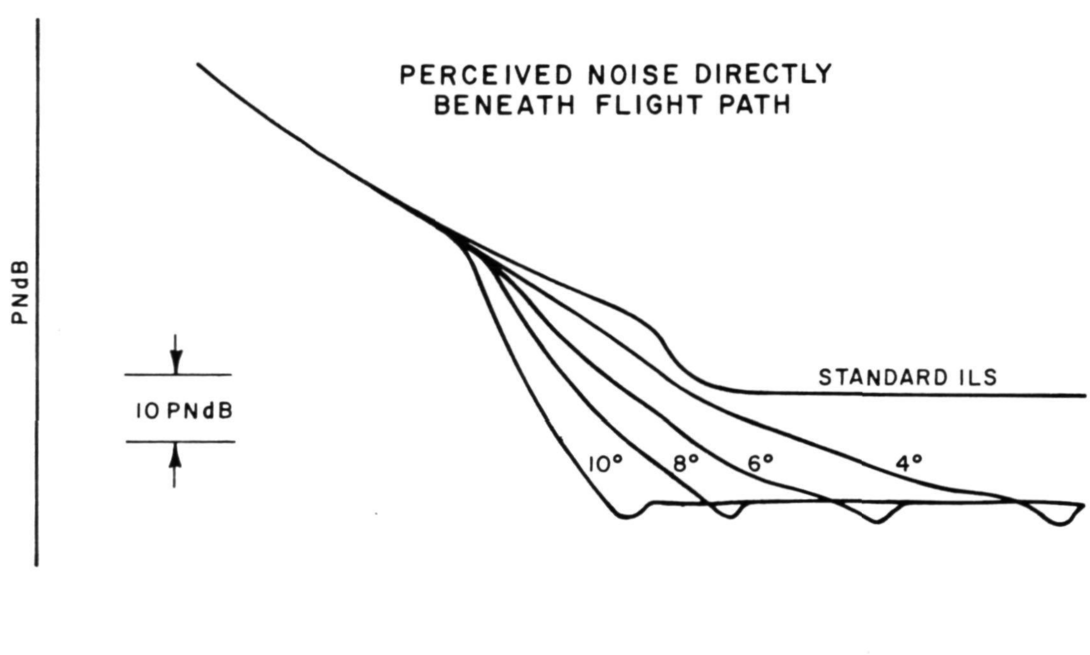


Figure 9 - Effect of Upper Segment Flight Path Angle on Perceived Noise Levels
(Data from simulator noise prediction system)

The tentative optimum angle determined in the Simulation Evaluation was 6°. This was confirmed to be the best compromise between operational acceptability and noise abatement in the Engineering Flight Evaluation. There was excellent correlation between the simulator and the aircraft regarding controllability, airspeed, and engine settings on the upper segment. The 6° upper segment provides good noise abatement and can be flown with 30° flaps in tailwinds as high as 20 knots with the throttles set enough above idle to provide acceptable thrust response.

It was determined in the simulator, and confirmed on the aircraft, that an upper segment angle which yields significant noise abatement is not compatible with the B-727 anti-ice minimum power requirements. At lighter gross weights the minimum requirement cannot be met even on a 5° upper segment.

Lower Capture Point and Transition

The lower capture point and transition are conceptually the same as the upper capture point and transition. The pitch up maneuver initiated at the lower capture point should place the aircraft on the ILS glide slope beam center without passing below it regardless of airspeed or wind speed. To meet these criteria, the capture point is determined as a function of rate of closure on the glide slope as well as displacement from it (Figure 10) in a manner similar to the determination of the upper capture point.

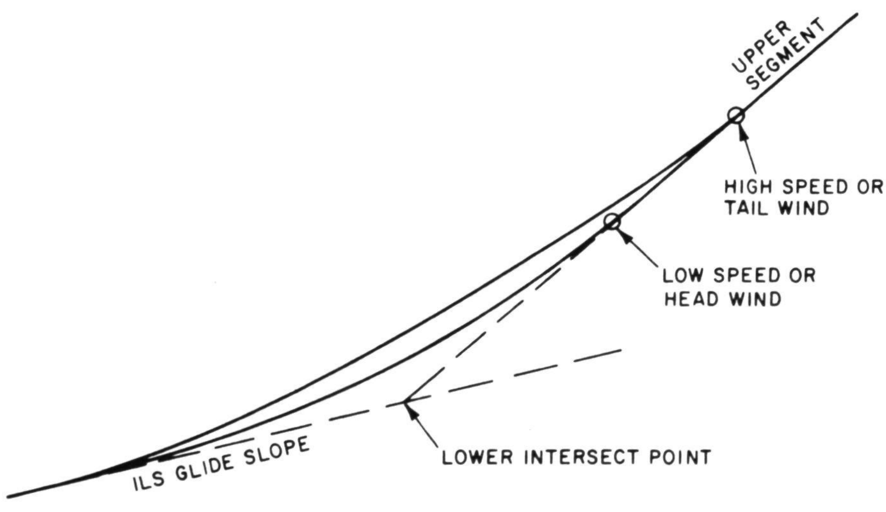
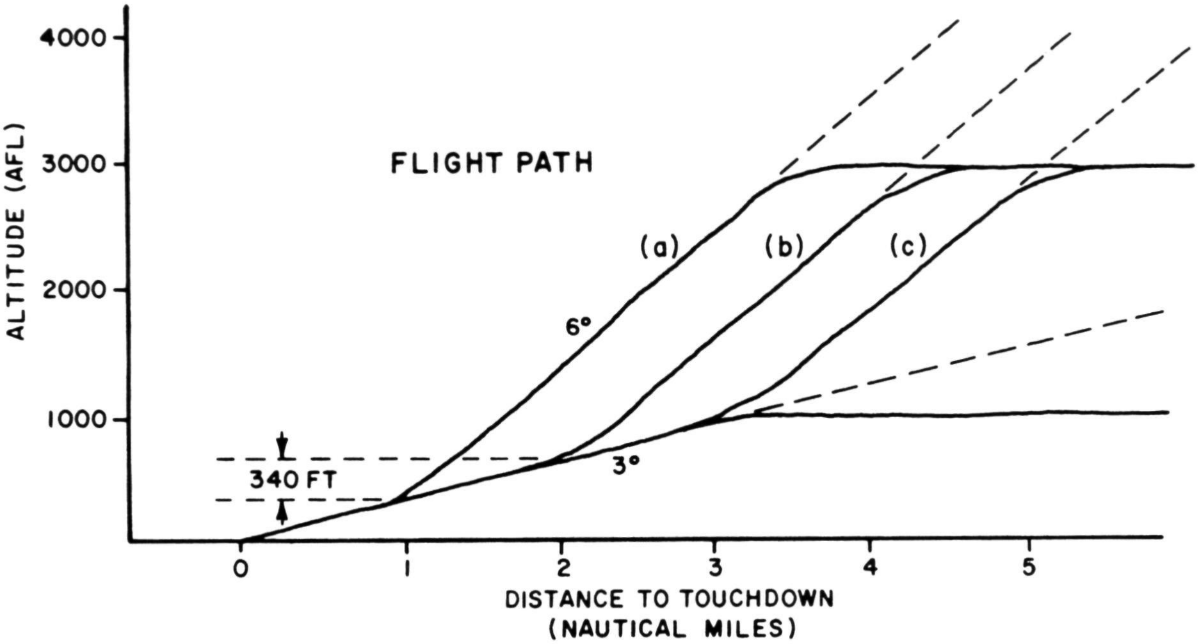


Figure 10 - Lower Transitions, showing variable lower capture points and location of Lower Intersect Point.

In the simulator the transition time (from capture point to "on glide slope") was varied from 10 to 30 seconds in steps of about 2 seconds with associated changes made in the lower capture point. The optimized transition time is about 24 seconds during which the required pitch attitude change is only 5° (3° of flight path angle change and 2° due to airspeed bleed). This results in a transition which is smooth, easy to fly, and virtually imperceptible to the passengers. Normal acceleration measured during the transition was typically less than .03 G. It requires from 250 to 500 feet of altitude to transition from the upper segment to the glide slope, depending on airspeed and winds.

Lower Intersect Point

The location of the intersection of the upper segment angle with the glide slope has a significant effect on noise levels (Figure 11), but, as with the upper segment angle, this must be weighed against operational constraints. The primary operational constraint is that some minimum time is required between stabilization on the glide slope and touchdown. Previous studies (refs. 6 and 8) in which lower intersect points 250 to 400 feet AFL were used have resulted in pilot apprehension about the safety of two-segment approaches, particularly in adverse weather conditions; these altitudes did not provide sufficient time after glide slope intercept to be stabilized for a safe landing. In the simulator, this parameter was varied from 280 to 830 feet AFL. Intersect altitudes from 500 to 1000 feet AFL were evaluated in the aircraft to verify simulation results.



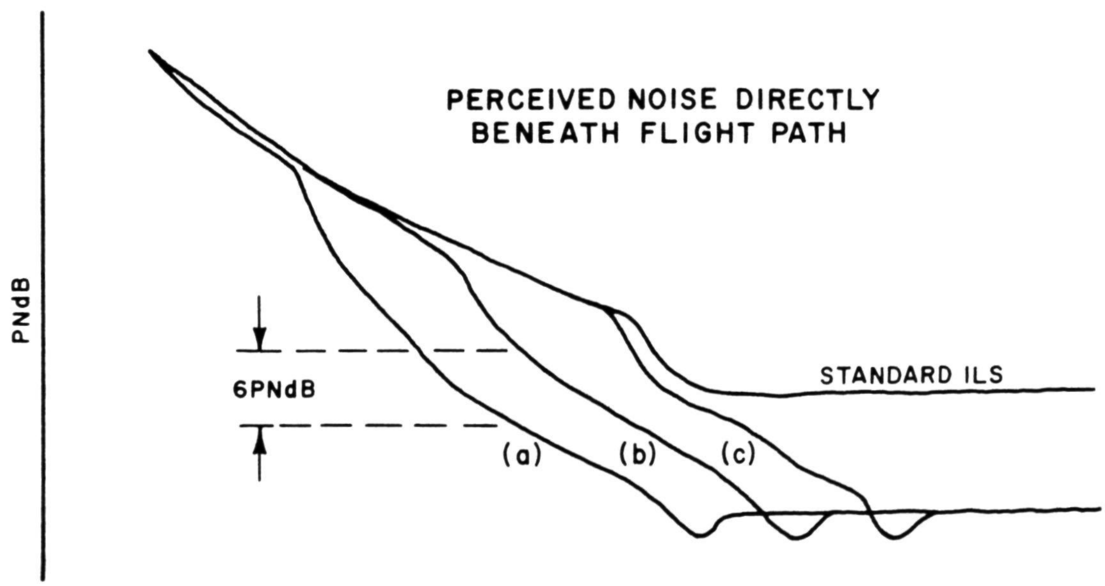


Figure 11 - Effect of Lower Intersect Altitude on Perceived Noise Levels
(Data from simulator noise prediction system)

After flying a number of profiles in which the lower intersect was varied, it was determined that about one minute of stabilization was required for a safe, comfortable approach. Stabilization on the glide slope by 500 feet AFL provided the necessary stabilized period. To arrive at this point on a 2.7° glide slope (the lowest flown during the evaluations) with the optimized lower transition, the lower intersect has to be at about 605 feet AFL. For higher glide slope angles the intersect altitude is higher since the upper segment is fixed in space with respect to the runway; for a 3° glide slope it is about 740 feet (Figure 12). The lower intersect altitude was defined as 690 feet AFL with respect to the 2.9° glide slope at Stockton, the primary evaluation airport.

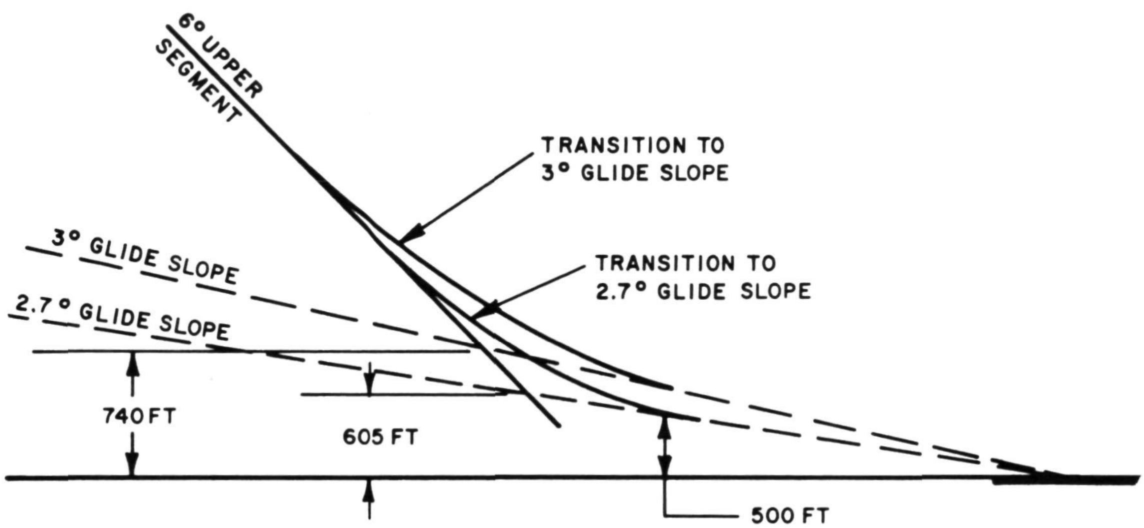


Figure 12 - Effect of Different Glide Slope Angles on Lower Intersect Altitude

Noise Abatement Results

Noise measurements made by Hydrospace Challenger, Inc. during both the Out-of-Service and In-Service evaluations verified that the profile provides significant noise abatement. Results indicate that, beyond 2.8 n. mi. from touchdown, a 6-8 EPNdB reduction is achieved under the path of the two-segment approach as compared to the standard ILS (refs. 15-17). Noise measurements of profiles differing from the normal profile were also made during the Engineering Flight Evaluation. These verified differences predicted by the simulator. Data taken at Los Angeles during the In-Service Evaluation confirmed out-of-service results.

PROCEDURES

System Arming

The normal procedure for preparing to make a two-segment approach was made to be similar to the procedure for a standard ILS approach. The appropriate ILS frequency is tuned and identified, the DME system is turned on, and the course and heading bugs on the HSI are set as for a standard ILS approach. Although most present ILS glide slope facilities do not include a collocated DME transmitter, it would be normal procedure to turn the DME on when available, regardless of the type of approach being made; for the two-segment system the collocated ILS-DME is required. The runway touchdown zone published on the approach chart (e.g., Figure 13) is set into the airport elevation panel to the nearest 10 feet. The flight director and/or autopilot are set to their respective auto-approach modes, with their altitude hold switches on. To this point, with the exception of entering the airport elevation, the procedure is identical to preparing for a standard ILS approach. If the pilot elects to make a Two-segment approach, he then arms the system by placing the two-segment selector switch in the ARM position.

When the switch is in the ARM position, the appropriate UPPER SEGMENT annunciators (flight director and/or autopilot) will illuminate amber confirming that all inputs are valid and the system is prepared to capture the upper segment. At this point the vertical deviation display on the HSI will indicate displacement from the upper segment.

Upper Segment Capture and Tracking

The HSI vertical deviation display comes into view from above as the aircraft approaches the upper segment. When the upper segment is about 1-1/2 to 2 dots above the aircraft, upper segment capture occurs. The flight director commands a pitch over and/or the autopilot begins pitching the aircraft nose down to transition to the upper segment. The UPPER SEGMENT annunciator switches from amber to green at this point. The deviation from the upper segment is displayed on a scale of 250 feet per dot. A larger scale (500 feet per dot) would provide a cue to the pilot that he was approaching the upper segment similar to the cue he has on a standard ILS approach, but the sensitivity would not have been adequate to provide good tracking of the upper segment.

The flaps are progressively lowered to 25° prior to capture. As the upper segment is captured, the landing gear is extended, the landing flap setting (either 30° or 40°) is selected, and the final descent checklist is completed. The 30° flap setting results in a lower thrust requirement on the upper segment, and therefore less noise, but in tailwinds in excess of 20 knots, 40° flaps are needed to keep the engines above idle thrust.

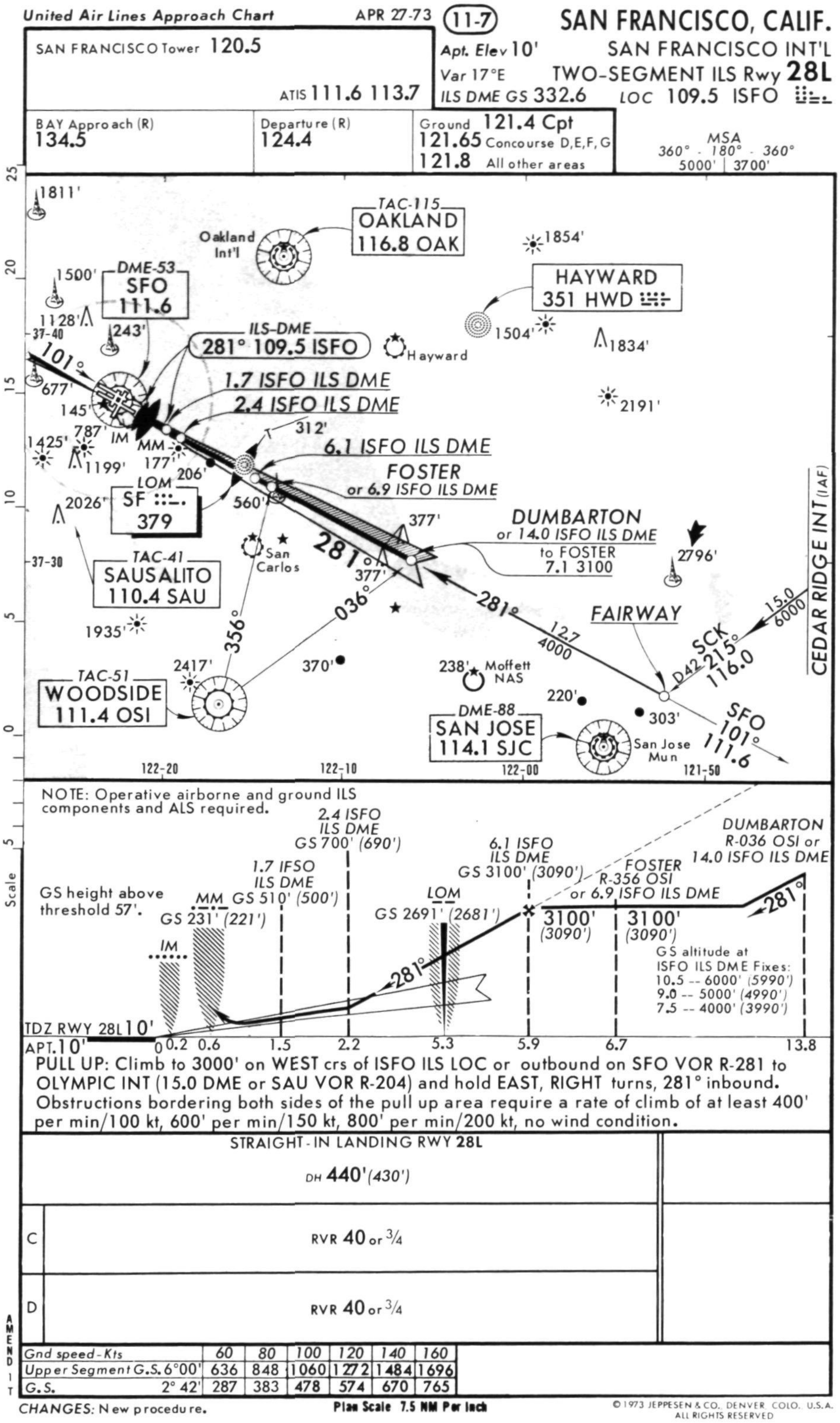


Figure 13 - Typical Approach Chart Adapted to the Two-Segment Approach (Reprinted by Permission - For Illustration Only, Not to be used for Navigational Purposes)

The system does not require localizer capture to furnish two-segment pitch guidance. However, at initial approach airspeeds greater than 180 knots, unsatisfactory upper transitions resulted if the localizer intercept angle exceeded 20° at upper segment capture. This is because the computer uses the rate of closure on the upper segment to determine the capture point (Fig. 8 Page 29). Under these conditions, the transitions were more abrupt than they should have been because the localizer intercept angle reduced the closure rate and thus moved the computed upper capture point closer to the upper segment than it should have been.

During the tracking of the upper segment the altitude at the outer marker is checked with the value published on the approach chart (Fig. 13), providing verification that the system is correctly positioning the upper segment. At 5 n. mi. from touchdown the GLIDE SLOPE annunciator illuminates amber indicating that the system is armed to capture the glide slope.

Glide Slope Capture and Tracking

The deviation display on the Attitude Director Indicator (ADI) indicates glide glope deviation whenever an ILS is tuned. During the transition from the upper segment to the glide slope, the indication is the same as the pilot normally sees during a capture of the glide slope from above. At glide slope capture, which occurs about 1 to 1-1/2 dots above the glide slope, the GLIDE SLOPE annunciator changes from amber to green and the HSI vertical deviation display is switched to indicate standard glide slope deviation.

Emergencies and Irregularities

The two-segment approach does not require any change in emergency or irregularity procedures. If an emergency or irregularity occurs while flying a two-segment approach, the pilot has every option available to him that he has during a standard ILS approach. Satisfactory two-segment approaches were made with a simulated engine failure during the Engineering Flight Evaluation. If, however, an abnormal situation requires an approach be made with less than 30° of flaps, a stabilized two-segment approach cannot be made. The drag of the landing gear and at least 30° flaps are required to stabilize on approach speeds on the upper segment with more than idle thrust.

Accuracy

Airborne and radar tracking data from 30 two-segment approaches made at Stockton during the Guest Pilot Evaluation was analyzed to determine the ability of the two-segment computer system to correctly define the upper segment. The average vertical navigation error (i. e. the difference between the upper segment position determined by the on-board equipment and the ideal upper segment position) and the root-mean-squares of the error are shown in Figure 14. The computed upper segment was, on the average, within 25 feet of the ideal upper segment. The potential sources of the error shown are DME system errors, altimetry system errors, computational errors within the computer, and inaccuracies in the radar tracking system.

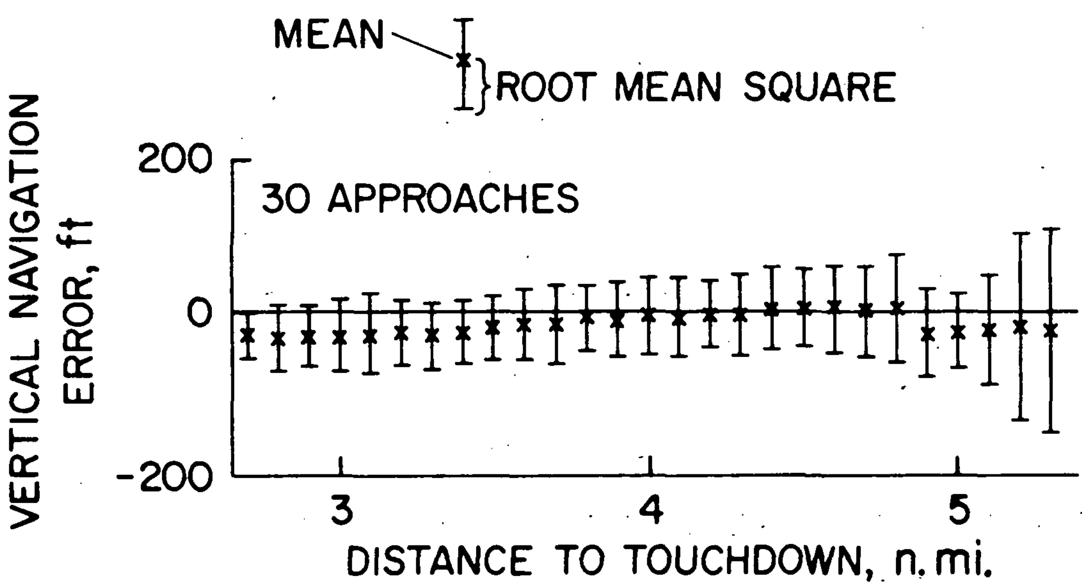
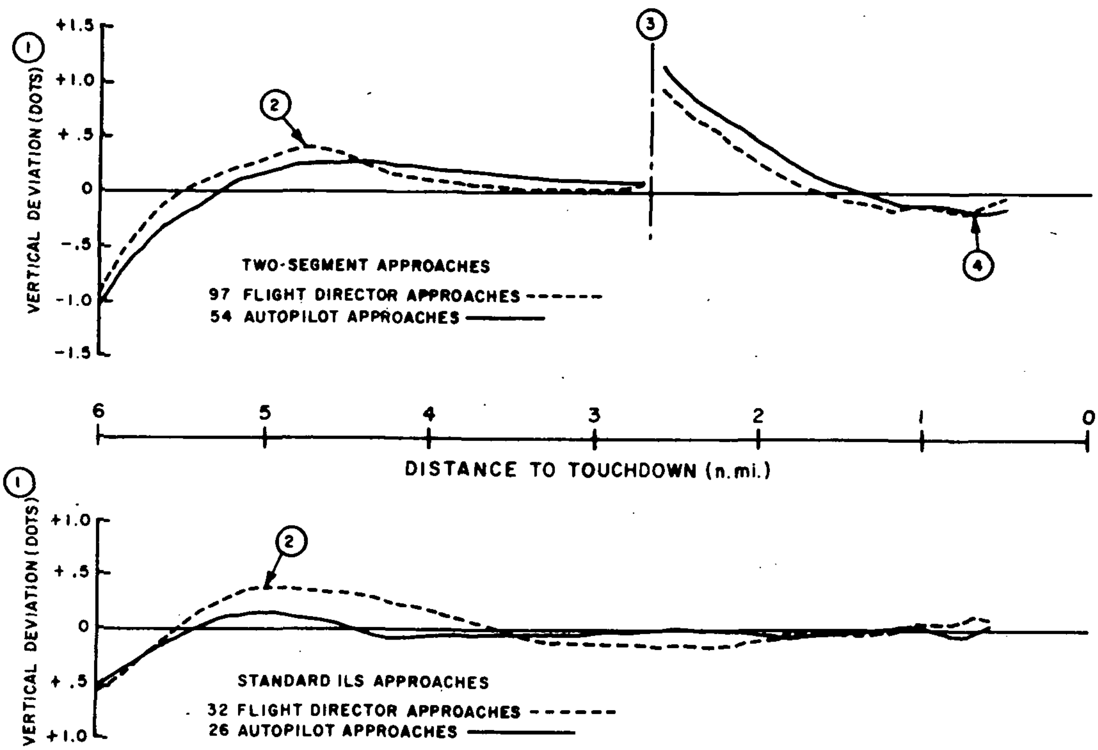


Figure 14 - Upper Segment Vertical Navigation Error

Vertical Tracking

A statistical analysis was made of the vertical tracking performance during the Guest Pilot Evaluation. (The detailed analysis is included in ref. 12.) A summary of this data is provided in Figure 15 which shows the performance in tracking the approach path determined by the on-board equipment as displayed on the raw deviation indications in the cockpit.



Notes

1 1 dot = 250 ft. on upper segment; .35° on ILS

2 Maximum average overshoots:
Two Segment Autopilot - .28 dot at 4.5 n. mi. (70 feet)
Two Segment Flight Director - .38 dot at 4.7 n. mi. (95 feet)
ILS Autopilot - .15 dot at 5.0 n. mi. (30 feet)
ILS Flight Director - .39 dot at 4.9 n. mi. (75 feet)

3 Nominal switch of vertical deviation indication from upper segment to glide slope (2.7 n. mi. from touchdown)

4 Maximum average overshoot below glide slope (.7 n. mi. from touchdown)
Autopilot - .21 dot (6 feet)
Flight Director - .16 dot (4 feet)

Figure 15 - Average Vertical Tracking Performance
(Ansett aircraft; Guest Pilot Evaluation)

The solid lines on Figure 15 show the average autopilot performance. On the standard ILS approach there is a small overshoot at the capture and a very small second overshoot. The second overshoot is too small to be noticed by the pilot. The glide slope tracking is very good. The initial overshoot for two-segment approaches is larger than on the ILS approaches. The autopilot does not converge all the way back to the upper segment, and the average deviation is still 1/8 dot (about 30 feet) high when the lower capture occurs and the HSI deviation switches to display glide slope. The autopilot completes the lower transition in approximately 1 n.mi. and the average value passes through the glide slope center line. The deviation never gets very large but it should converge back to the center line and not pass below it. This indicates that the glide slope signal attenuation in the two-segment computer could be improved within 1.5 n.mi. of touchdown.

The dashed lines on Figure 15 show performance of the flight director-pilot combination in tracking the desired path. The transition to the glide slope on standard ILS approaches results in about a 75 foot overshoot which is gradually corrected. A small overshoot below the glide slope center line occurs at 3.6 n.mi. The airplane is returned to the center line at 1.8 n.mi. and tracks the desired path well for the remainder of the approach. This is good performance and meets present criteria for low visibility flight conditions. On two-segment approaches the upper segment deviation moves across the HSI scale twice as fast as the glide slope does on standard ILS approaches. The capture point occurs at about 1-1/2 to 2 dots, depending on closure rate. The large scale and rapid movement of the deviation bar during the capture of the upper segment causes some difficulty when pilots attempt to use the movement of the bar as an indication to configure the airplane for the initial descent. The overshoot experienced on the two-segment approach is somewhat larger (95 feet) than on the standard ILS approach. The deviation converges to the upper segment centerline between 3 and 4 n.mi. Glide slope capture occurs at about 2.7 n.mi. from touchdown, at which time the transition to the glide slope is initiated and the vertical deviation indication switches to display the glide slope. There is a small overshoot of about 1/8 dot as the airplane converges on the glide slope and that small deviation holds throughout the rest of the approach. Although this is not as accurate as the standard ILS approach, it meets present criteria for low visability flight conditions.

A statistical analysis was also made of vertical tracking performance during the In-Service Evaluation. Although standard ILS approaches were not made during the In-Service Evaluation for comparison, the analysis provides a basis for comparing the performance of the system on the UA aircraft with that on the Ansett aircraft.

Comparing the average autopilot vertical tracking performance (solid lines) on Figure 16 with that on Figure 15 shows that the upper segment transition is very much improved on the in-service aircraft. There is no tendency to overshoot the upper segment, and the average deviation from the upper segment is only .055 dot, or about 14 feet. The autopilot still drops slightly below glide slope, indicating that additional fine-tuning of glide slope signal attenuation in the computer is required.

The in-service flight director-pilot vertical tracking performance is also much improved over that observed in the Guest Pilot Evaluation. The manually flown upper segment transition is slightly longer than the autopilot transition from 2 dots to .25 dot (2.1 n.mi. vs. 1.7 n.mi.) and .25 dot is corrected down to .05 dot much more gradually (1.7 n.mi. vs. .7 n.mi.). As with the autopilot, there is no tendency to overshoot the upper segment when the pilot flies the approach with flight director. (The initial approach altitudes for flight director approaches were 250 feet lower on the average than those for the autopilot approaches, which accounts for the displacement shown in Figure 16.) The pilot flown glide slope captures are also somewhat longer than the autopilot glide slope captures. Unlike the autopilot, the flight director approaches do not, on the average, go through the glide slope, but instead hold about .1 dot high after completion of the transition. The combined autopilot and flight director maximum deviations are also shown in figure 16. The difference between autopilot and flight director maximum deviations is small.

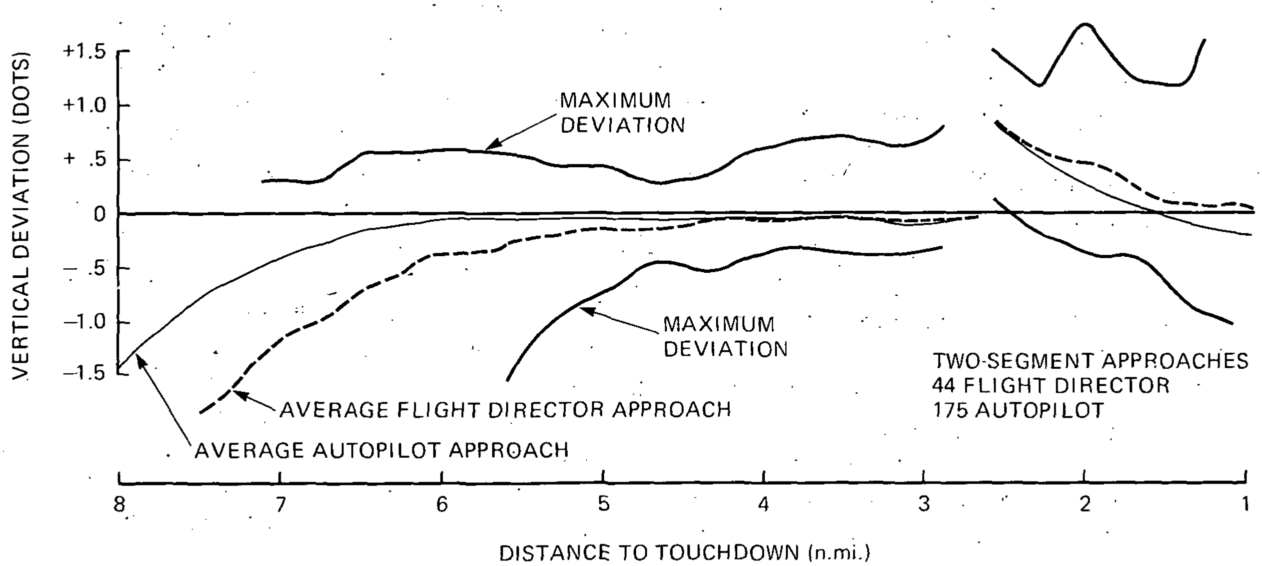


Figure 16 - Average Vertical Tracking Performance
(UA aircraft; In-Service Evaluation)

Examination of radar plots of approaches showing the actual aircraft deviation from the ideal two-segment path (Figure 17) confirmed that the autopilot approaches and the pilot flown flight director approaches are acceptably accurate for low visability flight conditions. In addition, radar plots from in-service two-segment approaches at Los Angeles were compared with plots of ILS approaches flown by other B-727-200's during the same period. These plots (seventeen of each approach type) showed that the glide slope portion of two-segment approaches averaged 7 to 13 feet below the ILS approaches and, although acceptable, this again showed that a minor adjustment of glide slope signal attenuation would be desirable.

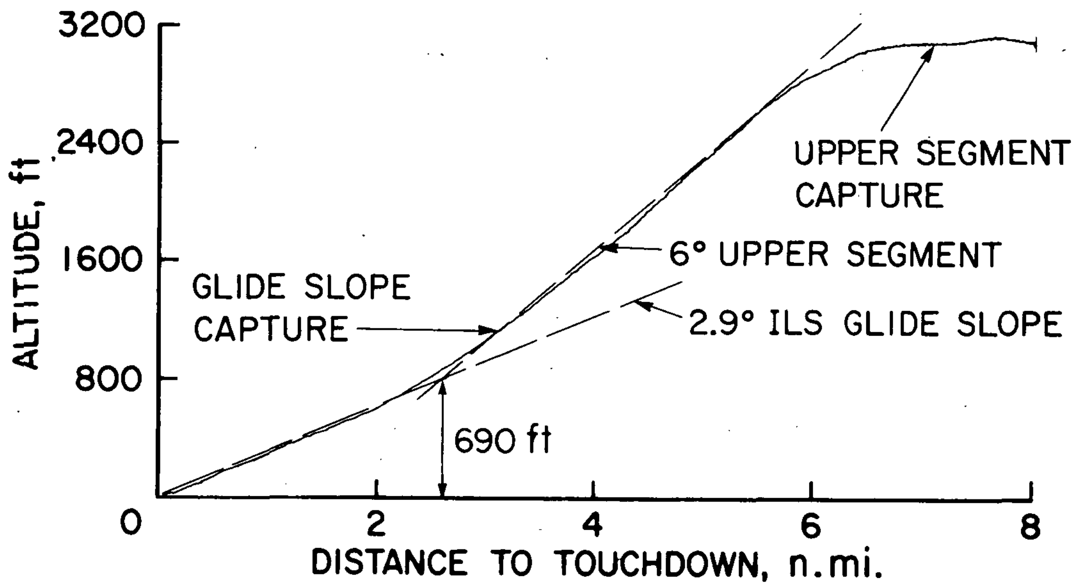


Figure 17 - Typical Radar Tracking Plot of a Two-Segment Approach
(Autopilot approach during Guest Pilot Evaluation at Stockton)

Autopilot Low Approach Performance

Three hundred auto-coupled approaches during the In-Service Evaluation yielded additional data on the acceptability of the system for operations to low weather minimums. Table II shows how the probability of completing a successful coupled approach increases as the aircraft nears touchdown. This indicates that the system detects failures early in the approach or that unacceptable performance is detected by the pilot early in the approach. The success of an approach was judged in the cockpit according to the following criteria.

1. The airplane is in trim so as to allow for continuation of normal approach and landing.
2. Indicated airspeed and heading are satisfactory for a normal flare and landing (speed must be within 5 knots) of programmed airspeed but not less than computed threshold airspeed).
3. The airplane is positioned so that the cockpit is within, and tracking so as to remain within, the lateral confines of the runway extended.
4. Deviation from glide slope does not exceed 1 dot (± 75 microamps) as displayed on the ILS indicator.
5. No unusual roughness or excessive attitude changes occur after leaving middle marker.
6. The autopilot does not unexpectedly disengage.

TABLE II - COUPLED APPROACH SUMMARY

Number of Auto-Coupled Approaches	Successfully Completed	Percent Successful
300 initiated	249	83.0
260 flown to 500 feet or lower	246	93.9
252 flown to 400 feet or lower	240	95.2
235 flown to 300 feet or lower	226	96.2
200 flown to 200 feet or lower	197	98.5
142 flown to 150 feet or lower	140	99.3
108 flown to 100 feet	108	100

Of the 17 approaches which went to 500 feet or lower and were judged unsuccessful, 11 were due to a poor DME transmitter at San Francisco, 4 were due to poor autopilot localizer captures, one was apparently due to ground traffic interference with the glide slope transmitter, and one was disengaged at the 500 foot protector due to displacement of the upper segment towards the runway due to the airport elevation set panel not being properly set. Only the latter one of these can be attributed to the airborne two-segment system. If two-segment equipment were permanently installed in the aircraft, a check of the airport elevation set panel would be added to the approach descent checklist to eliminate this problem. The cause of the DME problems at San Francisco was corrected early in the evaluation. All of the "unsuccessful" coupled approaches were completed either with the flight director only or visually.

During the entire six month In-Service Evaluation there was only one missed approach attributed to the system. This was due to a failure in the airport elevation panel which, in effect, displaced the upper segment so far away from the runway that when the system was armed, the aircraft was already well past the upper segment capture point. The system operated as designed in that it did not command a pitch down in an attempt to capture the upper segment from above and, if it had not been previously turned off by the flight crew, it would have automatically disengaged 1.8 n.mi. from touchdown.

System performance is acceptable for low weather minimum operations. However the system does not comply with the FAA's Category II Advisory Circular insofar as the FAA requires stabilization on the glide slope by 700 feet above field level.

Airspeed and Power Control

Two airspeed schedules were used during the Guest Pilot Evaluation. The pilot could add a 10 knot increment to the normal approach reference speed and bleed if off during the lower transition, or he could maintain the normal approach reference speed throughout the entire profile. In the first case the pilot must make a minor trim change and add a small amount of power during the lower transition, but airspeed control is easier to maintain on the upper segment. In the second case the pilot must add somewhat more power at the lower transition and must pay closer attention to the airspeed to hold it constant, but needs to make little or no trim change. Guest pilots were about evenly divided on whether to carry the 10 knot increment or fly a constant speed. In either case, more attention to airspeed is required during and after the transition since there is not as much time to establish airspeed on the glide slope as in a standard ILS approach. Line pilots seemed familiar enough with the aircraft that the two-segment did not introduce any significant difficulties in airspeed control. On the average, they bled off 20 knots of airspeed at a more or less uniform rate throughout the approach.

One of the concerns previously expressed regarding energy management aspects of the two-segment approach was that during the transition to the lower segment airspeed might drop below approach reference speed, thereby degrading safety; or that power in excess of that required on a standard ILS might be required to prevent such a loss of airspeed, resulting in an increase in noise levels. Figure 18 shows the results of an analysis of minimum airspeed versus approach reference speed during the transitions of 100 In-Service Evaluation approaches. There does not appear to be any tendency to drop below approach reference speed ($V_{ref\ app}$) during the transition. The noise data taken at Los Angeles during the In-Service Evaluation (ref. 17) shows no apparent tendancy towards higher noise levels at the transition. This is a result of the transition being gradual enough that airspeed can be controlled adequately with normal throttle position adjustments.

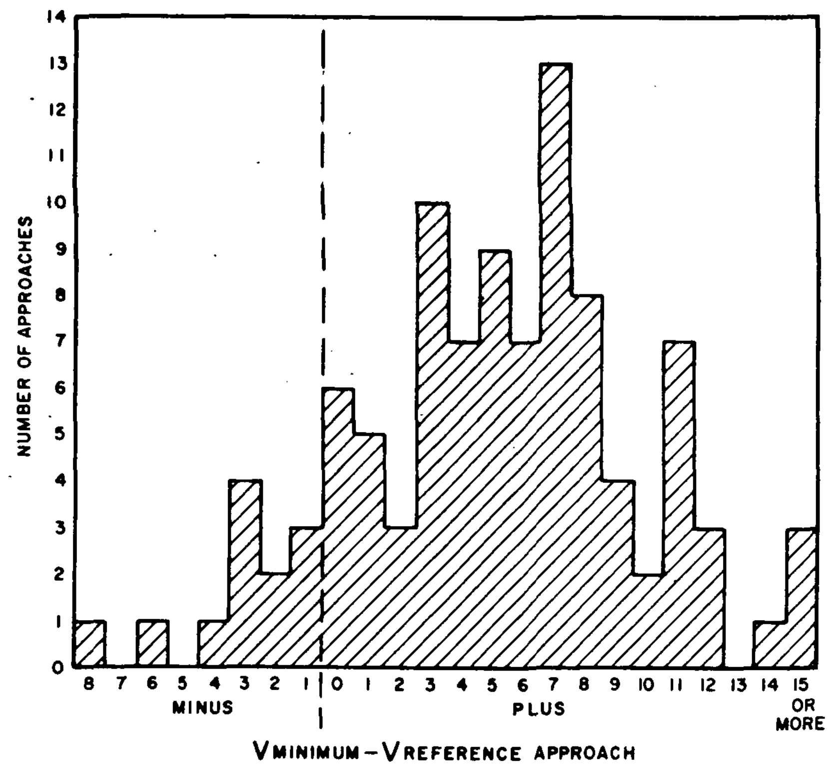


Figure 18 - Minimum Airspeed during Transition

Analysis of 100 In-Service Approaches: Difference between approach reference speed and minimum airspeed during transition. Note: Approach reference speed equals threshold reference plus 1/2 steady headwind component, threshold reference equals 1.3 times stall speed plus full gust value; Minimum airspeed read from data sampled every .1 n.mi. from glide slope capture to 400 ft. AFL.

PILOT ACCEPTANCE

One hundred twenty-five pilots flew two-segment approaches in various capacities during the program. The Project Pilot Team consisted of the Manager of 727 Flight Operations Development, the 727 Flight Training Manager, and five Project Pilots. Three Engineering test pilots, two from UA and one from FAA, were involved with the post-modification and certification flights. Fifty-seven pilots participated in the out-of-service Guest Pilot Evaluation, and 55 line pilots and three additional flight managers particpated in the In-Service Evaluation. All participants in the out-of-service evaluations are listed in Table III.

Guest Pilot Evaluation

The Guest Pilot Evaluation focused on whether the system which had been developed could be flown in line service. In rendering this judgement, pilots were asked to consider flight safety, the procedures and displays, and the profile. The approach syllabus flown by the guest pilots was specifically designed to facilitate comparison of the two-segment approach with the standard ILS approach.

The consensus of the guest pilots was that the two-segment approach was safe and easy to fly. There is a slight increase in workload over the standard ILS approach due to increased instrument scanning and airspeed control functions. Most felt that after a few approaches the average pilot would be familiar enough with the equipment to fly the procedure in instrument conditions with no degradation of required safety. An important factor in this judgement was the similarity to the standard ILS approach which had been designed into the equipment and procedures. A few felt that although the two-segment approach was not as safe as the standard ILS approach, it was acceptably safe in the majority of flight conditions encountered in airline service. The required level of safety is maintained if two-segment approaches are not used in icing conditions or extreme tailwinds. There were also a few who felt that the two-segment was safer than the standard ILS by providing a broader view of the airport environment and keeping the aircraft above general aviation traffic longer.

The use of autothrottles in conjunction with two-segment approaches did not significantly reduce the pilot workload. A few pilots thought autothrottles would be desirable in some conditions, but the consensus was that they are not required.

As expected, guest pilots had difficulty with the two-segment approach when tailwinds on the upper segment were greater than 20 knots. Under these conditions the throttles must be retarded to idle, and the rate of descent required to stay on the upper segment is unacceptable.

TABLE III- OUT-OF-SERVICE EVALUATION PILOTS

Project Pilot Team

- Tom Branch, UA Project Pilot
- Tony Brown, UA Training Manager
- Fred Drinkwater, NASA Project Pilot
- Hugh Monteith, UA Project Pilot
- John Morrison, UA Lead Project Pilot
- Floyd Snyder, UA Project Pilot
- Bob Stimely, UA Manager 727 Flight Operations Development

Test Pilots

- Jim Bugbee, FAA Engineering Pilot
- Bill Loewe, UA Engineering Test Pilot
- Larry Otto, UA Engineering Test Pilot

Guest Pilots

American Airlines
- Al Reeser, Director of Flight Engineering
- Bernie Wohl, Line Pilot

Ansett Airlines of Australia
- Dusty Lane, Flight Manager - Flying Standards

Braniff International Airways
- Bruce Douglass, Line Pilot, Instructor Pilot

Continental Airlines
- Carl Rogers, Assistant Flight Manager

Delta Air Lines
- Ray Daniel, Line Pilot

Eastern Air Lines
- Al Cleaver, Line Pilot
- Jim Cousins, Manager of Flying

Lufthansa
- Robert Salzl, B-727 Division Chief Pilot*

Northwest Airlines
- Don DeBolt, Fleet Manager - 727-707
- Ed Johnson, Training Manager - 727

Pacific Southwest Airlines
- Don Coney, Line Pilot

Pan American World Airways
- Jack Teters, Chief Training Captain

Trans World Airlines
- Gordon Granger, Director of Operational Research and Development

*Did not complete entire guest pilot syllabus.

TABLE III - OUT-OF-SERVICE EVALUATION PILOTS - Continued

Guest Pilots - Continued

United Airlines
- Bob Collins, Vice President Engineering
- Frank Cowles, Flight Manager
- George Henderson, Director Flight Operations Development
- Walt Matsui, Flight Manager
- Ernie Maulsby, Flight Manager
- Howard Mayes, Vice President Flight Technical Services
- Warren Mugler, Flight Manager
- Tat Tatman, Flight Test Captain
- Lloyd Treece, Regional Vice President Flight Operations
- Gene Tritt, Flight Manager
- Mel Volz, Flight Manager
- Gerry Zimmerman, Line Pilot

Western Airlines
- Ed Richardson, Line Pilot

Air Line Pilot Association
- Ernie Burmeister, United Airlines Line Pilot
- Jim Carlson, Northwest Airlines Lines Pilot
- Charlie Caudle, National Airlines Line Pilot
- Dag Dorward, United Airlines Line Pilot
- Wayne Fischer, Continental Airlines Line Pilot
- Jim Gates, United Airlines Line Pilot
- Joe Harris, Trans World Airways Line Pilot
- Ray Lahr, United Airlines Line Pilot
- Bill Lively, Continental Airlines Line Pilot
- Bob Patterson, United Airlines Line Pilot
- John Pieburn, Braniff Airlines Line Pilot
- Bruce Putney, Eastern Air Lines Line Pilot
- Jack Wilson, Pan American Airways Line Pilot

Air Transport Association
- Bill Russell, Manager of Navigation & Data Acquisition

Allied Pilots Association
- Frank McCormick, American Airlines Line Pilot

TABLE III - OUT-OF-SERVICE EVALUATION PILOTS - Concluded

Guest Pilots - Continued
Boeing Aircraft Company
Brien Wygle, Director of Flight Operations
Douglas Aircraft Company
Bill Casey, Engineering Test Pilot
Roger Sanders, Engineering Test Pilot
FAA
Jim Baker, Air Carrier Inspector
Ivan Behel, Air Carrier Inspector
Bob Chubboy, Flight Operations Program Officer
Joe Ferrarese, Assistant Chief Operations Division
Charlie House, Air Carrier Inspector
Gayle Mace, Operations Inspector
Phil Nisgore, Operations Inspector
Ralph Noltemeier, Chief, Flight Technical Programs
Sal Nucci, Engineering Specialist
Dick Sliff, Chief, Aircraft Engineering Division
Dick Skully, Director of Environmental Quality
US Air Force
Ken Dyson, USAF Test Pilot

After the pilots made several approaches, many found it significantly easier than anticipated. Analysis of the recorded data from flight director approaches shows that, after their second or third two-segment approach, most pilots were flying the approach within the same tolerances that they flew standard ILS approaches under the same conditions. There was increased acceptance of the procedures and techniques after the pilots had experience with the system. The stabilization period onthe glide slope prior to touchdown was considered sufficient because of the smooth transition to the glide slope and the positive guidance provided throughout the approach.

Although personal opinion differences existed regarding the display layout of vertical deviations, there was general agreement that the annunciation and instrumentation is satisfactory. Differing display philosophies are common among airlines and are typically accommodated by minor interface and equipment modifications.

In-Service Evaluation

Based on the results of the Out-of-Service Evaluations, the system was placed into revenue service for evaluation with the following restrictions:

1. Do not operate under conditions requiring full anti-ice capabilities.
2. Operate under conservative weather minimums for introduction into line service, until crew experience with the system is gained and equipment reliability is demonstrated.

The In-Service Evaluation concentrated on whether or not the pilot experienced any difficulties with the two-segment approach. There was a wide variety in the numbers of two-segment approaches completed by line pilots who flew the system as shown in Table IV.

TABLE IV - IN-SERVICE PILOT EXPERIENCE WITH TWO-SEGMENT SYSTEM

NUMBER OF TWO-SEGMENT APPROACHES	NUMBER OF PILOTS
1-5	27
6-10	12
11-20	8
21-30	6
35	1
41	1

Among pilots who flew the system and procedures, acceptance level was very high. Generally, the pilots accepted the two-segment approach as a valid and viable concept.

Most of the adverse comments received during the In-Service Evaluation related to specific equipment or coordination problems. A key question on the In-Service Pilot Questionnaire was: "Under the conditions which existed, would you rather have flown a standard ILS than the two-segment approach?" Table V is a month-by-month summary of answers to this question. In addition to those questionnaires on which it was indicated that the Captains did not have a preference, the question was not answered on about 10 percent of the questionnaires. Although a case could be made that the lack of a comment is more indicative of a positive feeling about the two-segment approach than a negative one, these latter were not included in the summary.

TABLE V - IN-SERVICE EVALUATION PILOT PREFERENCE FOR STANDARD ILS APPROACH

	YES	NO PREFERENCE	NO	% PREFERRING STANDARD ILS
May	13	1	51	20%
June	9	0	56	14%
July	6	6	74	7%
August	6	10	52	9%
September	8	3	46	14%
October	5	1	34	13%
October (last half only)	1	1	25	4%

The major problem evident from pilot comments during the first month was that additional coordination with air traffic controllers was required. Situations arose where controllers made requests which were incompatible with the clearance for a two-segment approach such as early turn-ins or high speeds. During the first week in June, the FAA familiarized the controllers with the two-segment procedure. Problems with ATC were rare thereafter. The FAA concluded from questionnaires administered to controllers after more than 400 approaches that the two-segment approach had a negligible impact on the Air Traffic Control system.

When placed into service on the UA B-727-200, there was an objectionable oscillation on the flight director command bars due to differences in instrument gains between the Ansett and UA aircraft. This oscillation was the source of numerous complaints with the system until the necessary adjustments were made in the computer late in the first month of the evaluation.

Several other equipment difficulties accounted for most of the adverse reactions to the system throughout the remainder of the evaluation. These difficulties included nuisance disengagements, unacceptable system performance after being armed early on the downwind leg, a jump in the flight director command at glide slope capture, and continued slight oscillations in the flight director commands. On numerous occasions, however, the pilots did not express a preference for the standard ILS approach in spite of encountering one of these problems.

From mid-September through the end of the program, most of the participating pilots had experience with the system earlier in the evaluation. They were familiar with the equipment and procedures and with the problems which had been encountered.

In mid-October, the equipment was modified to eliminate the nuisance disengagement and improve the flight director commands. After the modifications, only one adverse equipment comment out of 27 approaches was received. This one comment resulted from a situation when autopilot engagement was improperly attempted after upper segment capture. Flight director/autopilot disagreement was noted on only one of the 14 coupled approaches after October 15; this occurred when poor localizer tracking required disengagement of the system at 400 feet. There were no reports of the command bar jump at capture after the equipment was modified. The enthusiasm for the system which crews had displayed early in their experience with it seemed genuinely renewed after the system improvements which they had requested were incorporated.

After the pilots became acquainted with the system, the two-segment approach was generally accepted as just another routine operation. There was an eagerness among the crews to give the system a chance to perform, even after the novelty had worn off. This was particularly evident in situations where a special effort by the crew was required to obtain Air Traffic Control clearance to fly two-segment approaches.

At the conclusion of the evaluation, none of the participating line pilots disagreed with the conclusion that the procedures and profile are safe, easy to fly, and compatible with the airline environment.

AIRLINE ACCEPTABILITY CONSIDERATIONS

Passenger Acceptance

Previous studies (refs. 5 and 8) have indicated that the acceptability of the two-segment approach from the passengers' viewpoint is not a serious problem. Specific passenger evaluation during the Guest Pilot Evaluation and monitoring of passenger complaints during the In-Service Evaluation (during which an estimated 40 000 passengers flew on two-segment approaches) substantiated this conclusion. The g-force sensations experienced during transitions are no greater than those caused by normal VFR terminal area maneuvers, and the aircraft pitch attitudes and rates of descent are not of any apparent concern.

Category II Applicability

The demonstrated system accuracy is suitable for Category II operations. However, several issues regarding the applicability of the system are not yet resolved. The evaluation was limited to a single system which interfaced with the autopilot and the Captain's flight director only. The acceptability for Category II of an installation in which one flight director system is kept independent of the two-segment system was not determined. Other potential options for Category II installations include a system which returns all approach authority over to existing Category II hardware after glide slope capture without any significant guidance discontinuities, or full dual installations. In the latter case a means would have to be found to cope with maximum allowable input differences between independent altimetry and DME systems which would result in as much as a 1-1/2 dot difference (worst case) between independent dual systems' determination of the upper segment location.

Line Maintenance Capabilities

The ability to make line maintenance tests on the system and interface is essential in regular air carrier service. This should provide troubleshooting capability to the unit level such that a faulty unit can be isolated, replaced, and the system operation verified during a 30-minute line turnaround.

While the test set used in the evaluation was excellent for analyzing and testing the prototype system, it is too complex and time-consuming to be practical for use in line maintenance operations, which require timely maintenance action within a short turnaround period. The test set provided the level of detail typical of overhaul or base maintenance.

The system should incorporate some level of Built-In-Test-Equipment (BITE) and maintenance annunciators which will assist in the isolation of the faulty unit. The practical level at which BITE would be required would be resolved between the equipment manufacturer and the prospective air carrier customer, and through the interaction of the competitive market environment.

Additional Equipment Considerations

The following additional development or product improvement areas to make the system more acceptable to the air carriers remained at the completion of the evaluation.

As previously discussed, the short-term solution to the nuisance disengagement problem involved the use of radio altimetry. For the reasons stated earlier, an alternate solution which does not require radio altimetry should be found.

In the prototype equipment, the system was designed to not accept autopilot engagement after passing the upper segment capture point even though the pilot might have intercepted upper segment on flight director and subsequently wished to couple the autopilot. Minor logic revisions to the system could retain the capture from above and overshoot protection and still permit the pilot to couple the autopilot after glide slope capture.

During the In-Service Evaluation the system disengaged on several approaches at San Francisco at altitudes from 150 to 350 feet as a result of loss of DME validity. The problem was corrected by adjusting the DME transmitter, but the experience pointed out a deficiency in the system design. DME is used for autopilot gain programming on the glide slope but not for primary guidance calculations. Auto-disengagement on the glide slope due to an invalid DME signal should be inhibited and a reversionary means of glide slope gain programming should be developed, such as altitude above field level (AFL).

In today's airline maintenance environment, the system equipment must be designed to interface with Automatic Test Equipment (ATE) to facilitate back-shop maintenance at the component level.

Financial Implications

A study was made of the implications of installing two-segment approach equipment suitable for use to Category II weather minimums on a fleet of aircraft (ref. 14). The cost of retrofitting UA's B-727-200 aircraft with dual two-segment approach systems is estimated to be about $37 000 (1973 dollars)

per aircraft. This figure is based on the assumption that out-of-service and training costs could be minimized by installing the equipment at airframe overhaul and including training with regular recurrent training programs. It does not include the costs of such product improvements as BITE, interface with ATE, etc.

Approximately 40 percent of the cost is for the two-segment avionics. The remainder is split approximately equally (20 percent each) among:

1. Engineering, modification, and installation labor.
2. Installation materials and modifications to existing equipment.
3. Spare equipment for line support.

Wide variations in the total retrofit costs should be expected for other carriers due to different fleet sizes and varying requirements to modify interfacing systems.

The recurring maintenance costs of new avionics systems are extremely difficult to determine. It is estimated, however, that maintenance costs would be of about the same magnitude as the potential economic benefits which accrue from fuel savings, based on 1973 fuel costs. Although not rigorously investigated in this program, a fuel savings may be realized due to the reduced thrust levels used during two-segment approaches. Due to the current interest in this subject, more careful investigations should be made before definite conclusions are drawn.

Timing

The time required to develop any necessary ARINC specification on the technical characteristics of the system is estimated to be at least one year. During that time, development work could no doubt go forward in solving some of the shortcomings which still exist with two-segment avionics, but procurement, design, and planning could begin only after a specification is developed.

The most severe restriction to the installation cost estimate above is that it does not include any aircraft out-of-service costs, by assuming that the system can be installed concurrent with aircraft overhaul. Such an assumption implies that the last aircraft installation would not be completed until ten years or more after the first installation. Accelerating the modification schedule to the minimum possible completion time, approximately two years, would require removing aircraft from service specifically for the work. This could increase the overall fleet retrofit cost by as much as 50 percent.

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